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MEASUREMENT OF HYDRODYNAMIC FORCES AND MOMENTS AND FLOW FIELD MAPPING OF A MODEL IN CONING MOTION

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THOMAS JOHN ECCLES

Submitted to the Departments of Ocean Engineering and Mechanical Engineering
on 25 April 1990 in partial fulfillment of the requirements for the
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Abstract

A method of captive model testing using an axisymmetric marine vehicle model in steady motion with constant roll and yaw rates has been used experimentally to obtain functional relationships between certain motion parameters and the resultant hydrodynamic forces and moments on the body. Specifically, cross coupling terms in roll rate and yaw rate have been investigated for non-planar cross-flow. An instrumented slender body of revolution with length/diameter of 9.5 was tested at Reynolds number of about 5 million, based on length. The tests were conducted at free stream velocity of 25 ft/s for coning angles between zero and -20° in 2° increments, at rotation rates of up to 200 rpm in 12.5 rpm increments in both rotational directions. The character of force and moment terms varying with rotation rate and coning angle was determined. The results may be translated to functional relationships between the hydrodynamic coefficients and the angular velocities in roll and yaw. The data showed a transition in the forms of the sway force and the pitch moment after the coning angle exceeded -10°, due to body lift in the cross flow.

A method for measuring the velocity field about the model using laser doppler velocimetry has been developed. The flow field was mapped for two model coning angles at one moderate rotation rate. The flow field representation portrays perturbations in cross flow velocity at five sections in a body-fixed reference frame. This method is useful in understanding the vortex mechanisms at work to influence body forces and moments. The data showed formation of asymmetric body vortices after the coning angle exceeded -10°.

Thesis Supervisor: Dr. J. E. Kerwin, Professor of Naval Architecture
Thesis Reader: Dr. H. K. Kytömaa, Assistant Professor of Mechanical Engineering

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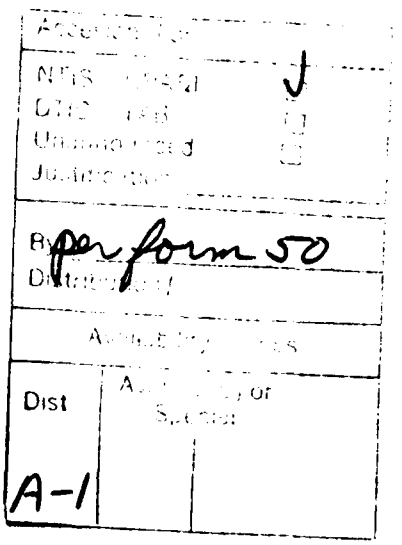

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My most sincere gratitude is owed to my wife Jennifer whose unfailing support and enthusiasm has provided me with inspiration at all the right times.

Nomenclature

A	Frontal area of hull = $\pi d^2/4$ (in feet^2)
B	Model buoyant force
BMC	Balance moment center (0.895 inches aft of the COR, on the x axis)
CB	Center of buoyancy of the model
CG	Center of mass of the model
COR	Center of rotation, the reference point for all measured and calculated forces and moments, located 11.31 inches aft of the model bow, on the x axis
d	Hull maximum diameter = 2.695 inches
g	Gravitational acceleration = 32.18 ft/sec^2
K,M,N	Hydrodynamic moments about the x, y and z body axes, respectively
K',M',N'	Dimensionless moment coefficients corresponding to K,M, and N
L_a	Length aft of parallel midbody
L_f	Length forward of parallel midbody
L_{pmb}	Length of parallel midbody
l_1	Hull length = 23.5 inches
l_2	Hull length in feet

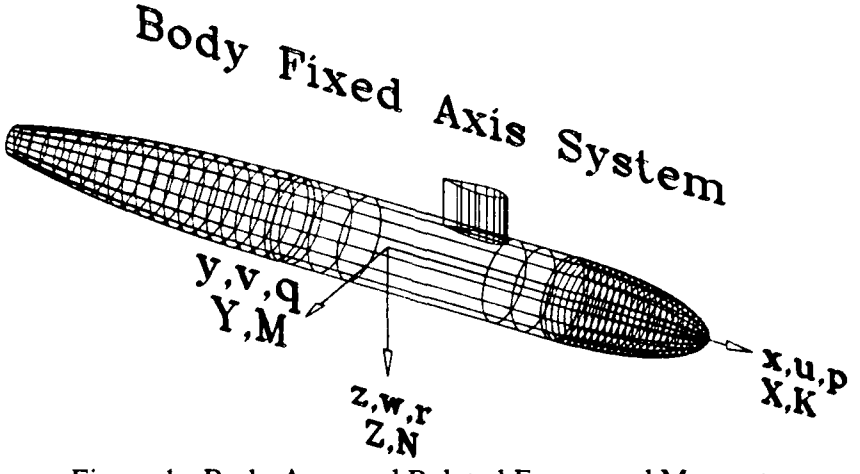


Figure 1: Body Axes and Related Forces and Moments

LDV	Laser Doppler Velocimeter
m	Model mass
p,q,r	Angular velocity components about the x, y and z body axes, respectively
rpm	Rotation rate in revolutions per minute
u,v,w	Velocity components along the x, y and z body axes, respectively
u_o,v_o,w_o	Velocity components along the x_o, y_o and z_o tunnel axes, respectively

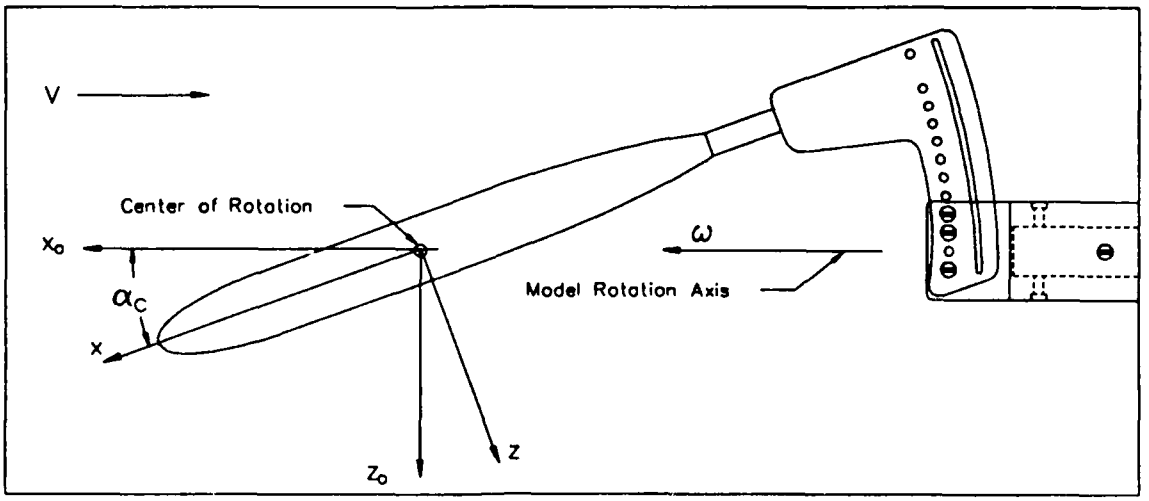


Figure 2: Body-Fixed and Tunnel-Fixed Coordinates [1]

U_∞	Tunnel free stream velocity
W	Model weight = mg
x,y,z	Right-handed, rectangular body-fixed axes with origin at the COR and positive directions of x toward the bow, y to starboard, and z down through the keel
x_o,y_o,z_o	Right-handed, rectangular tunnel-fixed axes with origin at the COR and positive directions of x_o colinear with the tunnel longitudinal centerline, directed into the free stream, y_o to starboard in the horizontal plane, and z_o vertically down
X,Y,Z	Hydrodynamic forces along the x, y and z body axes, respectively
X',Y',Z'	Dimensionless moment coefficients corresponding to X,Y, and Z
α_c	Coning angle, measured from the x_o axis to the x axis
ν	Kinematic viscosity of fresh water = $0.9733 \cdot 10^{-5}$ ft^2/sec
ρ	Density of fresh water at 77°F = 1.9348 slugs/ft^3
φ,θ,ψ	Roll, pitch and yaw angles about the x, y and z body axes
φ_o	Roll angle about tunnel-fixed x_o axis
ω	Model rotation rate about x_o axis = $d\varphi_o/dt = 2\pi$ rpm/60
$\vec{\omega}$	Model rotation vector in tunnel-fixed axes = $\omega \hat{i}_{x_o}$
ω'	Dimensionless rotation rate = $\omega l_z/U_\infty$

Chapter 1

Introduction

This research program is an effort to improve understanding of the hydrodynamic effects of flow about a submersible marine vehicle in a complex motion which may be described as non-planar with respect to the free stream. Experiments are conducted to determine the relationships between a combination of roll and yaw rates and the hydrodynamic forces and moments e .perienced by the vehicle. These relationships may be quantified and used to improve the performance of computer-based vehicle motion predictors.

Measurement of the flow velocity at points around the vehicle may provide insight to understand the processes which result in the perceived forces. A method of measuring the perturbation velocities about a vehicle in steady non-planar motion is presented. This introductory chapter will describe the basic nature of the problems to be solved and the methods available for solution.

1.1 Captive Model Testing

Naval architects historically have depended on scale model testing to prove the feasibility of hull designs by experimentally measuring the dynamic performance of the model in water. In recent years, computer based models have been used for motion prediction. Computer synthesis of a hull design is generally cheaper and much faster than physical model building, and on-line testing gives the designer more rapid feedback of performance.

The accuracy of analytical models which use series expansions of generalized equations of motion depend on the validity of the coefficients used to weight the series terms and the degree of expansion included in the series. The coefficients are usually derived from empirical data taken in captive model tests and full-scale experiments. The level of detail in higher order terms included in the expanded equations of motion is determined by the synthesis model designer and is usually limited by the availability of empirical data which would validate the weighting coefficients of the higher order terms.

A typical problem of developing coefficients may be examined to illustrate a motivation for this research. The forces and moments experienced by a marine vehicle in six degrees of freedom may be expressed as a set of nonlinear differential equations. Taking as a zero condition the instantaneous surge velocity $u(t)$, with all other velocity components zero, the forces are:

$$\begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} = f(u, v, w, p, q, r) = \frac{1}{2}\rho A U^2 f'(Re, v', w', p', q', r') \tag{1}$$

where

$$Re = \frac{Ul}{\nu}$$

is the Reynolds number.

Using the notation of reference [2] to abbreviate partial differentiation, the method of Taylor series expansion for these analytic equations gives

$$\begin{Bmatrix} X' \\ Y' \\ Z' \end{Bmatrix} = \sum_{k=0}^{\infty} \frac{1}{k!} \left(v' \frac{\partial}{\partial v'} + w' \frac{\partial}{\partial w'} + p' \frac{\partial}{\partial p'} + q' \frac{\partial}{\partial q'} + r' \frac{\partial}{\partial r'} \right)^k f'(Re, v', w', p', q', r') \tag{2}$$

As noted in reference [3] the inclusion of series terms beyond third order does not improve accuracy significantly. Abkowitz has shown that the symmetry of ship geometries about

the xz plane requires that X', Z' and M' are even functions of v', p' and r', and Y', K' and N' are odd functions of v', p' and r' [4]. This reduces the terms in equations (2) to a more manageable number, but the experimental determination of coefficients is not trivial.

Traditional experimental methods of measuring model response to various flows have relied on straight towing or rotating arm test facilities. The motions produced with these types of equipment are limited in that the roll component of angular velocity is zero, and the cross-flow velocities are restricted to parallel planes along the ship length. Terms in the equations of motion which require experimentation which controls roll rate and the construction of nonplanar cross flows are significant in modelling many types of vehicle dynamics. A facility which provides for control of these variables is the Coning Motion device at MIT's Marine Hydrodynamics Laboratory.

1.2 General Motion of Coning

With the advance of vehicle performance level requirements the demand for motion predictors to take account of so called "higher order effects" and coupling terms has increased. An example of a significant dynamic motion effect which was not included in rudimentary systems of equations is the coupling of yaw rate and pitch rate which causes a finned body in an ordered flat turn to pitch and experience a change in depth.

The captive model test method described here as coning motion was first investigated for aircraft in the 1920's by aeronautical engineers using a combination of roll and yaw rates to generate a steady motion of the vehicle in a direction which was never coplanar with the flow. The locus of model axis motion is a cone oriented with its longitudinal axis parallel to the free stream. The motion may be described as "coning motion" and is portrayed in Figure 3 below.

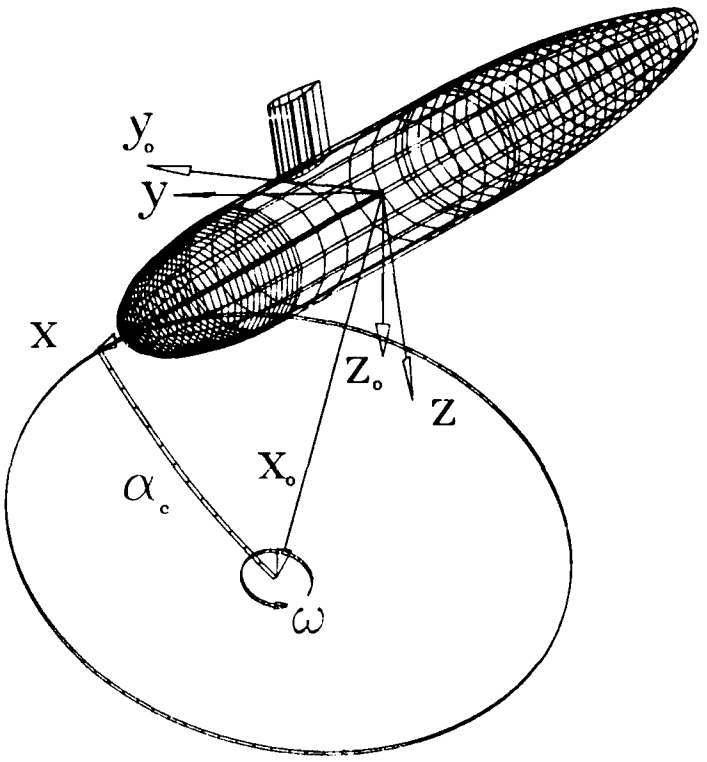


Figure 3: General Motion of "Coning"

In this figure, the constant angular displacement of the model from the free stream axis is the coning angle α_c and the driving motion is the rotation ω about the direction of the free stream. Thus for $\alpha_c = 0$, the model motion is purely a steady roll ($\varphi_o = \varphi$). The rotation may be decomposed as a combination of roll rate and yaw rate as

$$p = \omega \cos \alpha_c \qquad r = \omega \sin \alpha_c \tag{3}$$

Other "coning motion" degrees of freedom have been considered in aircraft tests in aerodynamic facilities. These include variations of the sideslip angle and the displacement between the model's center of rotation and the rotational axis of the system. In this hydrodynamic test those parameters are held to zero. The facility could be modified to account for the added complexity, but given the cross-section constraint in the tunnel, a shorter model (and thus lower Reynolds number) would be required for adding an axis offset.

The facility developed in previous work on this project by Johnson is the first implementation of a coning motion experiment for marine vehicles in water [1]. This thesis describes the first program to gather data using the apparatus over the full range of its operation.

Chapter 2

Test Apparatus for Force and Moment Measures

This chapter provides a description of equipment and systems used in experiments which measured hydrodynamic loads on the model. The development of the Coning Motion Apparatus used at MIT's Marine Hydrodynamic Laboratory is described in detail in reference [1]. This thesis presents the first comprehensive test program conducted using the Coning Motion system.

2.1 Model

The model used for force and moment measurements is an instrumented version of the standard (l/d = 9.5) body of revolution used in previous studies at MIT and elsewhere [5, 6, 7, 8]. Figure 4 and Table 1 provide gross model characteristics. A detailed discussion of the internally mounted 6-component balance in this model may be found in reference [1]. The internal model arrangement is shown in Figure 5.

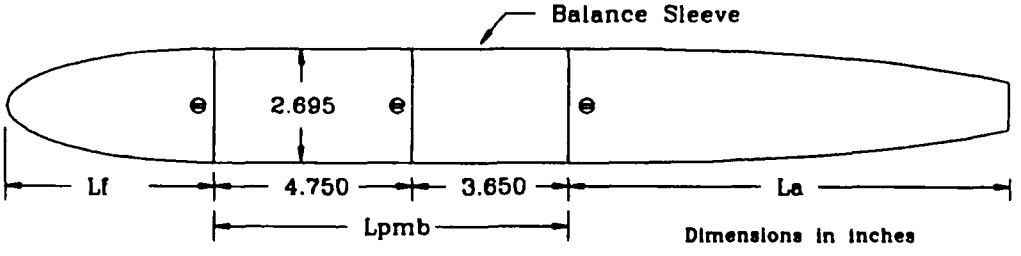


Figure 4: Model Dimensions [1]

Table 1: Instrumented Model Characteristics

Length / Diameter	9.5 inches
Length	23.50 inches
Diameter	2.695 inches
Weight	10.45 lbs
Buoyancy	3.23 lbs
Parallel Midbody (as a % of L)	39.6 %
Length Forward	4.85 inches
Length Aft	10.25 inches

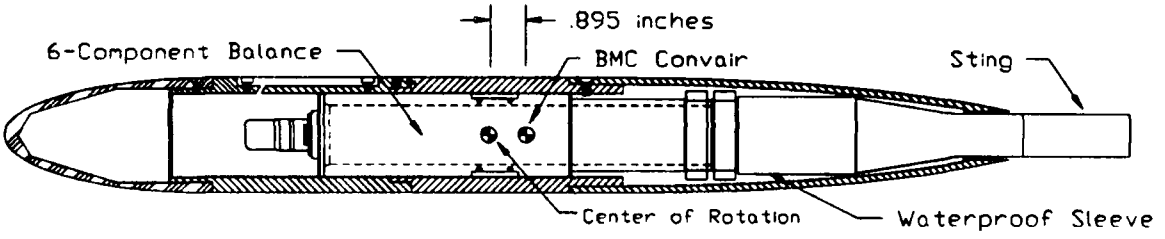


Figure 5: Model Internal Arrangement [1]

2.2 Facility

2.2.1 Tunnel

Testing was performed in the MIT Marine Hydrodynamic Laboratory's variable pressure water tunnel. The tunnel has a square cross-section test area with 20 inch sides. Limits on the model coning angle ($\alpha_{c\ max} = \pm 20°$) are based on physical interference with the tunnel wall. The tunnel generates flows of over 30 feet per second.

2.2.2 Rotating Mechanism

The coning motion rotating mechanism is installed through the downstream end of the water tunnel. A belt-driven axle penetrates the tunnel at the aft wall through the flow-turning vanes, and is aligned parallel with the flow and colinear with the central axis of the test section. A 2 horsepower stepping motor drives the axle through a changeable sheave for different speed ranges. The forward end of the driven axle is supported at the downstream end of the tunnel test section by a bearing inside a streamlined housing which bolts into the tunnel walls.

The model is mounted on a "sting" which is set into the adjustable sector piece at the forward end of the driven axle. Figure 5 shows the model (without appendage) mounted with the sector at a coning angle of -20°. The coning angle is adjusted between test runs by removing four machine screws, sliding the sector/sting/model assembly to a new α_c, and reinstalling the screws through the new hole alignment.

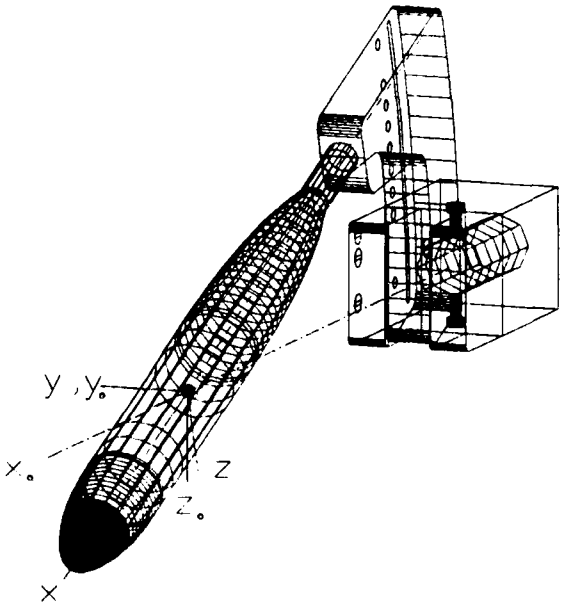


Figure 6: Model in Coning Motion Apparatus

In Figure 6, the model longitudinal axis is x, and the system rotates about the tunnel/flow axis x_o. The angular displacement between x and x_o is the coning angle α_c.

2.3 Data Acquisition System

The data acquisition system is built around an IBM PC XT computer which obtains data from the model instruments, a tunnel pressure sensor, and a 12 bit shaft encoder. The pressure sensor produces a signal proportional to free stream fluid velocity, and the encoder provides shaft angular position indication. The encoder output is also used to determine shaft rotation rate. Figure 7 is a schematic view of the principal components of the data acquisition system and their interconnections.

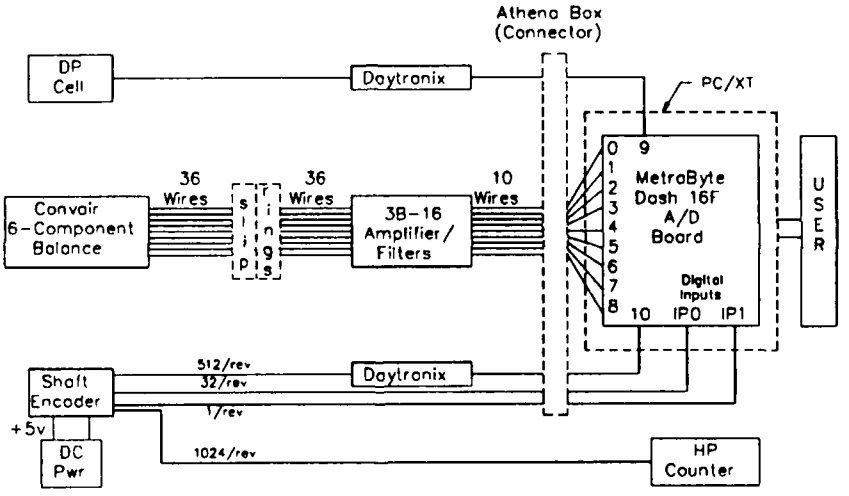


Figure 7: Data Acquisition Systems [1]

The model instrument signals are routed via a set of slip rings through signal conditioners to the analog-to-digital (A/D) converter board in the PC XT. Several encoder channels are fed to the PC XT, as is the differential pressure signal for tunnel velocity. The program logic which controls dynamic load testing makes use of the encoder signals to determine a reference position in shaft rotation, and then to key the data taking cycle of the

A/D board. A complete listing of Fortran code used in the experiments is included in Appendix D. Most of the force and moment software was developed directly from Johnson's preceding work to demonstrate the apparatus.

Chapter 3

Procedures for Force and Moment Measures

The steps involved in the force and moment measurement experiments are described in this chapter. A method of organizing the large number of repetitive experiments for efficient accomplishment by a team of four is presented. The tests may be characterized by the state of the model and the type of data being collected. The tests conducted at zero rotational speed to measure weight and buoyancy are referred to as static tests. The rotational experiments are dynamic tests: either inertial tests if conducted in air, or hydrodynamic tests if conducted in water.

Calibration of the Daytronix 9170 and 9140 signal conditioners used to amplify and convert the tunnel differential pressure sensor and encoder rotation rate signals was conducted daily, or after a long break during the day. The calibration coefficients were saved for pairing with the tests by date (to allow for post-processing of the load data).

3.1 Static Tests

The goal in this experiment is to isolate flow-related hydrodynamic effects; therefore an accounting must be made of the model's weight, buoyancy and inertia effects. For each coning angle, a zero rotation rate measurement of forces and moments was made in air at 32 evenly spaced intervals around one revolution (i.e., every 11.25°). A similar measure was made with the tunnel filled with water. For each case, an averaged set of "zeros" was determined by averaging the load outputs for each instrument over one revolution. Both the raw data and the averaged values were saved.

The zeros files were used later by the dynamic testing software to reduce the raw loads by the effect of gravity or gravity plus buoyancy, where appropriate. Inertia effects were determined during dynamic tests without water around the model.

3.2 Dynamic Testing

Dynamic tests were conducted by first measuring the inertial loads sensed by the model in the absence of water, then subtracting those, as well as the static components of weight and buoyancy, from the results measured in water to yield loads due solely to hydrodynamic effects.

The measurement of inertial loads was essentially identical to testing in water, except the tunnel facility was drained during the tests. The data gathering software stored results of the tests in files labeled with a first letter "I". These inertia load files were called later by the hydrodynamic test software, and their force and moment component values were subtracted from the associated measurements made in water.

Hydrodynamic tests involved the following basic procedure (items parenthesized are omitted for in-air tests):

- Set the coning angle (and fill the tunnel with water)
- (Set water tunnel flow rate to 25 ft/sec)
- Turn the model drive motor on to the desired rotation rate
- Run the program "DC" which requires responses to calls for
  - the calibration coefficients file
  - the static loads file for this coning angle
- The following data files will be produced during the several minutes required to run DC:
  - Raw data file containing all instrument values measured during the ten full rotations about the tunnel axis
  - Summed and averaged list of instrument values
  - Net of appropriate "zero" values

- Final loads measured in pounds of force and inch•pounds of moment after converting net "counts" data to dimensional values

For high rotation rate tests (>125 rpm), a different sheave was used on the motor drive shaft and a special hydrofoil was attached to the sector portion of the coning motion apparatus. The combined effect was to reduce the load on the motor so that the full range of rotation rates could be achieved. The foil's location nearly a foot downstream of the model ensured negligible foil effect on the test. With the foil installed and the motor shut down, a tunnel flow of 25 ft/sec would autorotate the model/sector assembly at about 125 rpm.

3.3 Test Program

The test program for measurement of forces and moments was conducted by a team of four. The test schedule was coordinated within a Program Matrix (see Table 2 below) which described an ordered method of accomplishment. The order was based on optimizing test conduct time by reducing the number of cycles of filling and draining the tunnel facility. Each number in the matrix represents the chronological order of a pair of tests (one in each rotational direction). The tests labeled "In Air" are inertial tests and those labeled "In Water" are the corresponding hydrodynamic load tests. Late in the program, as time remaining became a consideration, a decision was made to reduce the number of remaining tests by foregoing certain matrix elements. Identification of those tests was based on maintaining an equal distribution of data in both rotational directions, and ensuring even coverage through the entire range of coning angles.

The team followed a detailed procedure checklist to maintain a standard and formal laboratory routine. The checklist covered calibration, static testing, dynamic testing, model

Table 2: Test Program Matrix

Test Order as a Function of Rotation Rate and Angle of Attack

Rotation Rate (rpm)	TESTS IN AIR - Coning Angle α_c										
	0°	2°	4°	6°	8°	10°	12°	14°	16°	18°	20°
0.0	341	307	273	239	205	171	137	103	69	35	1
12.5	342	308	274	240	206	172	138	104	70	36	2
25.0	343	309	275	241	207	173	139	105	71	37	3
37.5	344	310	276	242	208	174	140	106	72	38	4
50.0	345	311	277	243	209	175	141	107	73	39	5
62.5	346	312	278	244	210	176	142	108	74	40	6
75.0	347	313	279	245	211	177	143	109	75	41	7
87.5	348	314	280	246	212	178	144	110	76	42	8
100.0	349	315	281	247	213	179	145	111	77	43	9
112.5	350	316	282	248	214	180	146	112	78	44	10
125.0	351	317	283	249	215	181	147	113	79	45	11
Add Wing and Large Sheave											
137.5	363	329	295	261	227	193	159	125	91	57	23
150.0	364	330	296	262	228	194	160	126	92	58	24
162.5	365	331	297	263	229	195	161	127	93	59	25
175.0	366	332	298	264	230	196	162	128	94	60	26
187.5	367	333	299	265	231	197	163	129	95	61	27
200.0	368	334	300	266	232	198	164	130	96	62	28

Rotation Rate (rpm)	TESTS IN WATER AT 25 FT/SEC - Coning Angle α_c										
	0°	2°	4°	6°	8°	10°	12°	14°	16°	18°	20°
0.0	352	318	284	250	216	182	148	114	80	46	12
12.5	353	319	285	251	217	183	149	115	81	47	13
25.0	354	320	286	252	218	184	150	116	82	48	14
37.5	355	321	287	253	219	185	151	117	83	49	15
50.0	356	322	288	254	220	186	152	118	84	50	16
62.5	357	323	289	255	221	187	153	119	85	51	17
75.0	358	324	290	256	222	188	154	120	86	52	18
87.5	359	325	291	257	223	189	155	121	87	53	19
100.0	360	326	292	258	224	190	156	122	88	54	20
112.5	361	327	293	259	225	191	157	123	89	55	21
125.0	362	328	294	260	226	192	158	124	90	56	22
Add Wing and Large Sheave											
137.5	369	335	301	267	233	199	165	131	97	63	29
150.0	370	336	302	268	234	200	166	132	98	64	30
162.5	371	337	303	269	235	201	167	133	99	65	31
175.0	372	338	304	270	236	202	168	134	100	66	32
187.5	373	339	305	271	237	203	169	135	101	67	33
200.0	374	340	306	272	238	204	170	136	102	68	34

and tunnel set-up between tests, and recording of data onto serialized portable storage media (360 KB floppy disks). A record book was kept with a data sheet for each α_c and ω combination.

Chapter 4

Test Results: Forces and Moments

This chapter presents the results obtained from hydrodynamic load experiments, and describes the methods used to obtain dimensionless parameter values from the summarized raw data.

4.1 Data Reduction

The hydrodynamic load files (one for each combination of coning angle and rotation rate) representing forces and moments in dimensions of pounds force and inch•pounds of moment were compiled for summarizing in dimensional and non-dimensional form. Forces, moments and rotational frequency were converted to dimensionless coefficient form by the following relationships:

$$Y' = \frac{Y}{\frac{1}{2}\rho A V^2} \qquad M' = \frac{M}{\frac{1}{2}\rho A l_1 V^2} \qquad \omega' = \frac{\omega l_2}{V} \tag{4}$$

The resulting coefficients are generalized for length, maximum diameter and free stream velocity, but are characteristic of the particular slender body form of this model. The results show variation of these coefficients with coning angle and rotation rate.

4.2 Results

The force and moment measurement results may be illustrated concisely by Figures 8, 9, 10 and 11. These surfaces represent the strength of dimensionless forces and moments with respect to coning angle and dimensionless rotational frequency.

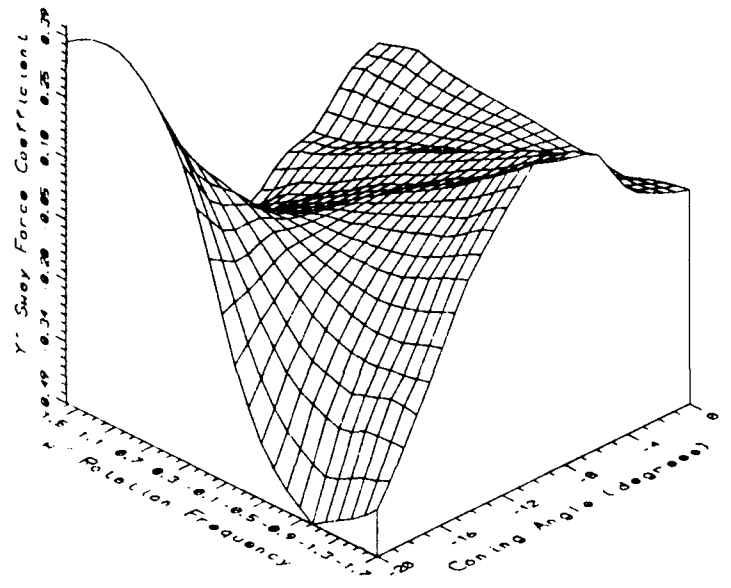


Figure 8: Sway Force Coefficient, Y'

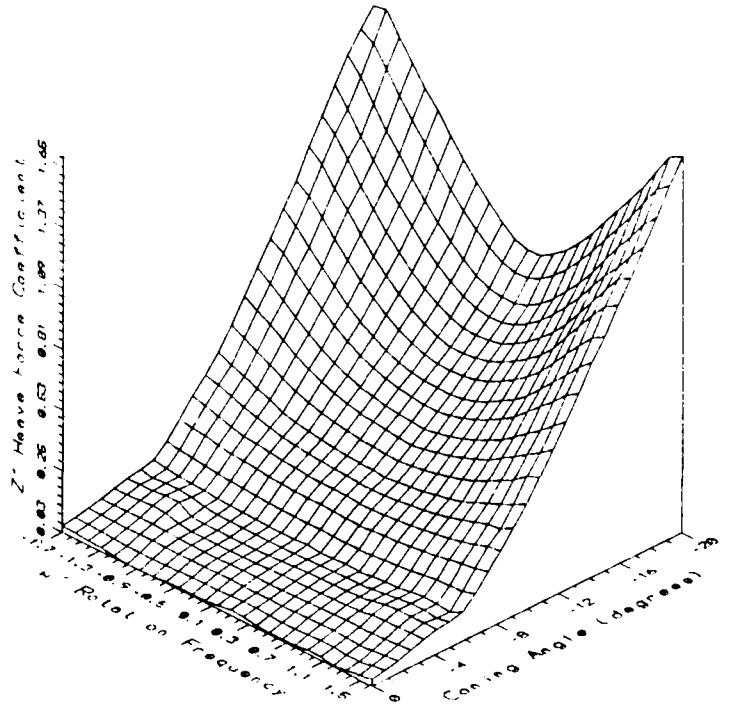


Figure 9: Heave Force Coefficient, Z'

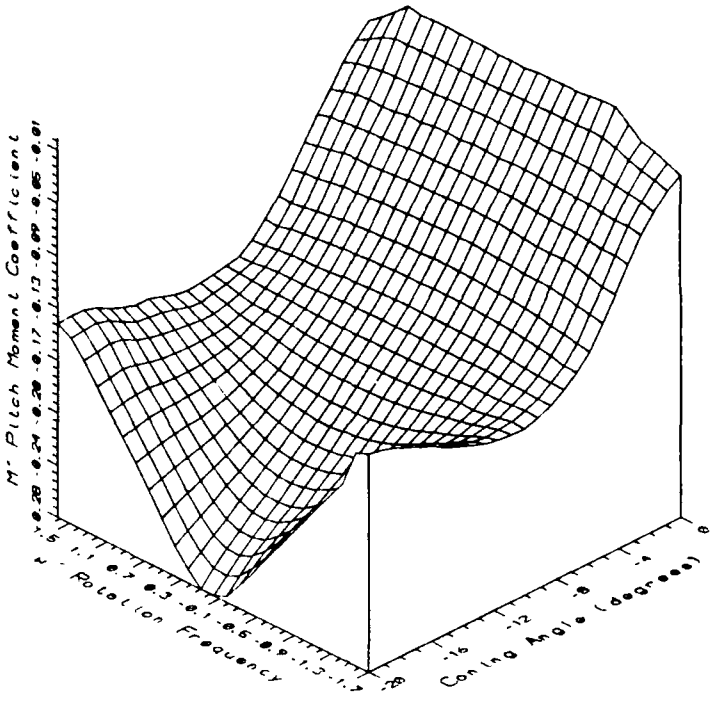


Figure 10: Pitch Moment Coefficient, M'

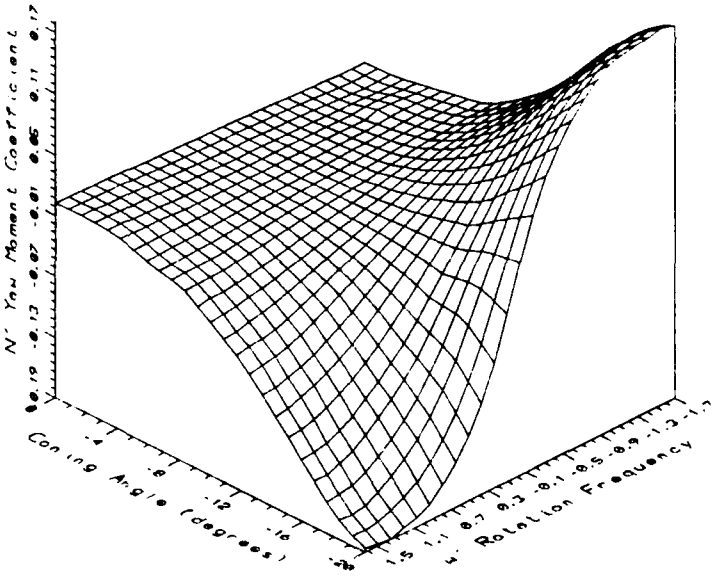


Figure 11: Yaw Moment Coefficient, N'

The next sets of graphs examine the data from two orthogonal perspectives. Variation of tangential and normal forces with rotation rate and coning angle are given in Figures 12 and

13. Figures 14 and 15 show variation of the related moments with the same parameters. These figures cover the range of coning angles from -10° to -20°. The results for smaller coning angles follow similar trends, and are presented in Appendix B.

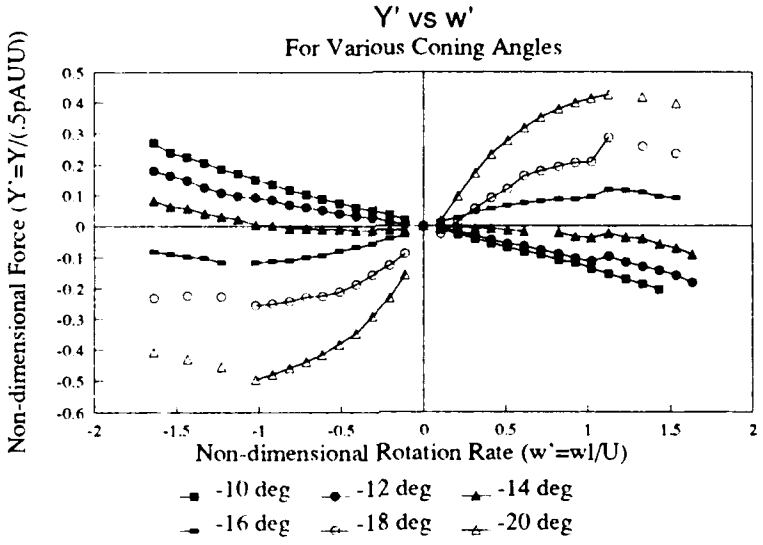


Figure 12: Sway Force, Y′ vs. ω′

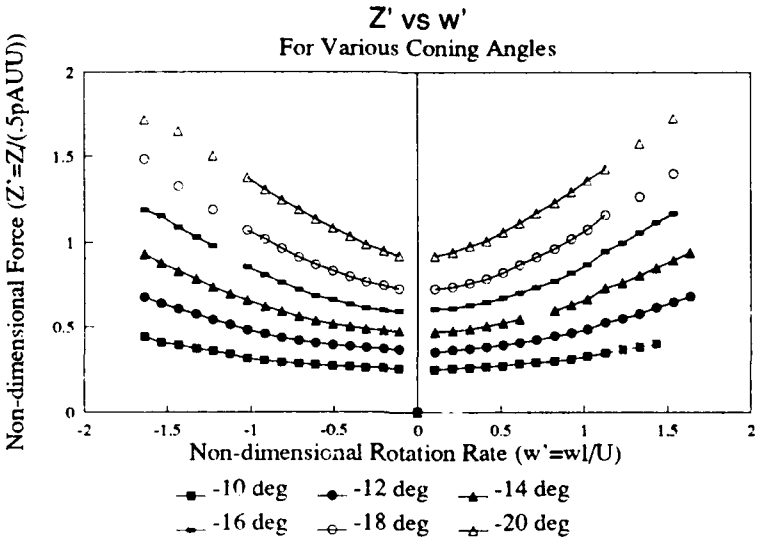


Figure 13: Heave Force, Z′ vs. ω′

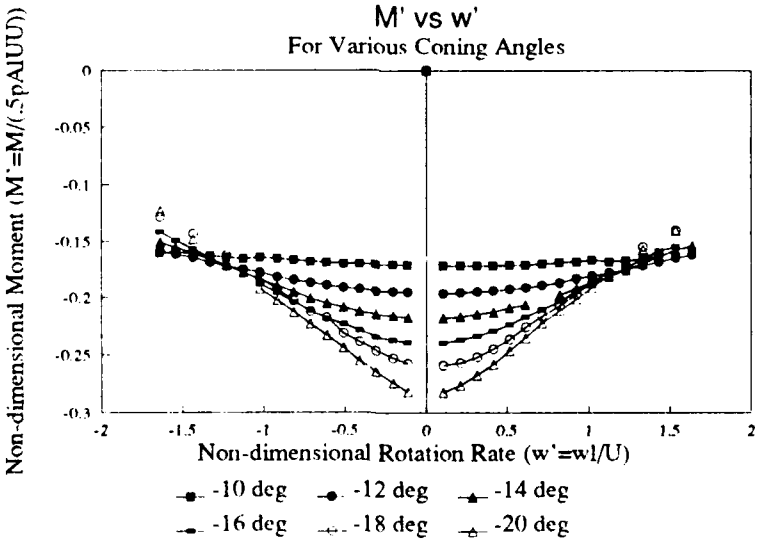


Figure 14: Pitch Moment, M′ vs. ω′

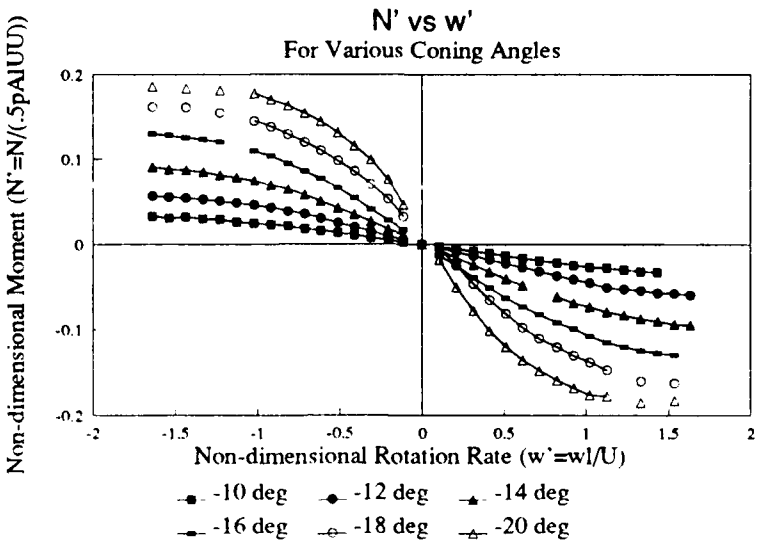


Figure 15: Yaw Moment, N′ vs. ω′

An orthogonal presentation of data (forces and moments versus coning angle) is given in figures 16, 17, 18 and 19 for a range of positive rotation rates. The results for opposite rotational direction are essentially identical, except for the asymmetry of odd functions.

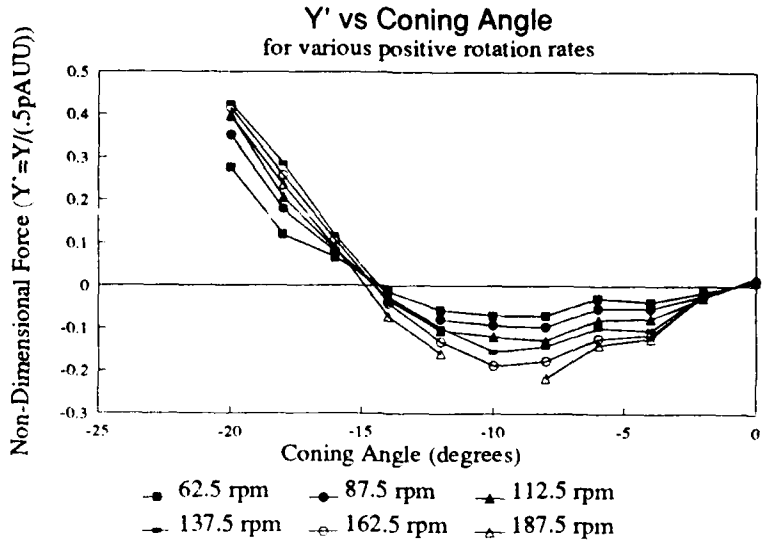


Figure 16: Sway Force, Y′ vs. α_c

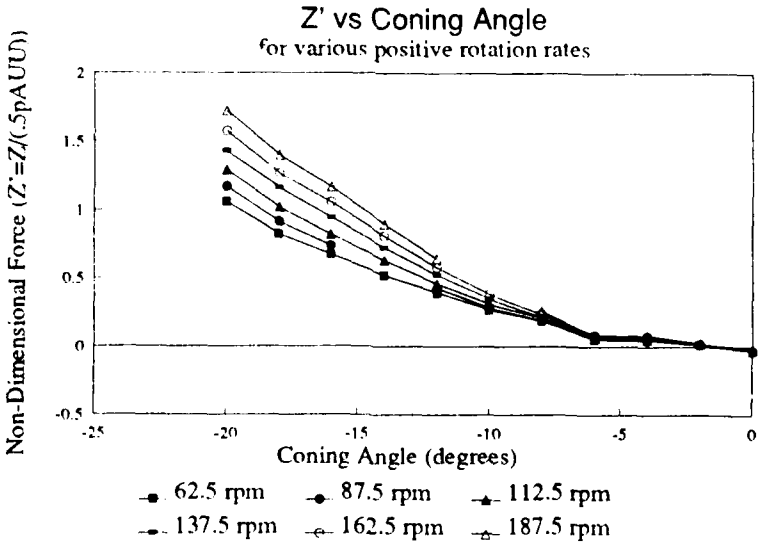


Figure 17: Heave Force, Z′ vs. α_c

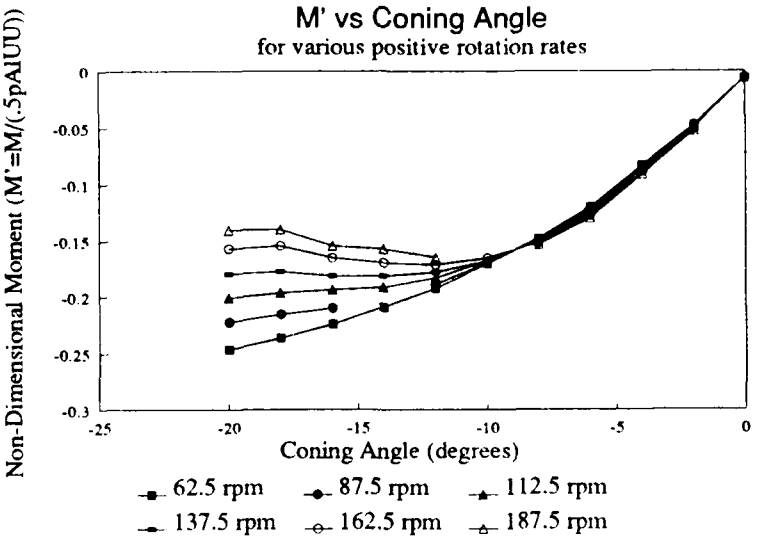


Figure 18: Pitch Moment, M′ vs. α_c

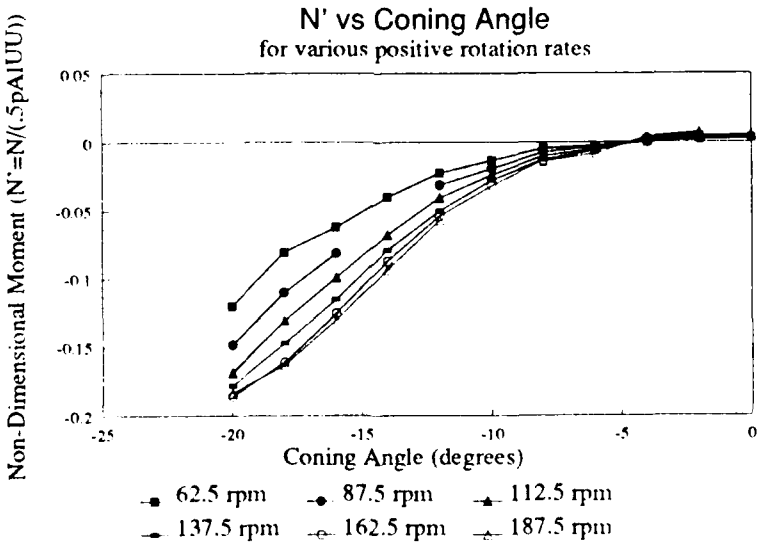


Figure 19: Yaw Moment, N′ vs. α_c

The summarized test data are presented in detail in tabular form and as graphical images for each coning angle in Appendix B.

In comparison with data obtained using the same equipment in April 1989 , the test data seem consistent and repeatable. Figures 20 and 21 show the correlation at a coning angle used by Johnson in the proof of concept work (α_c = -14°).

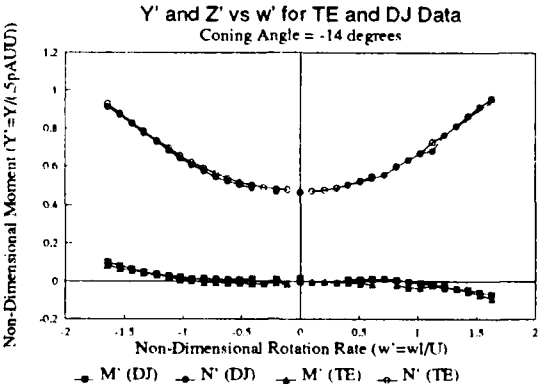


Figure 20: Comparison of Force Data

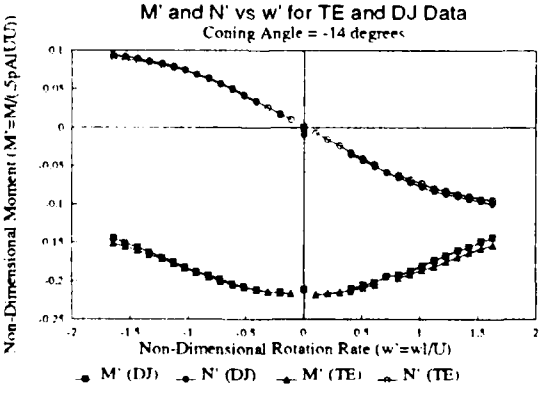


Figure 21: Comparison of Moment Data

4.3 Interpretation

The data seem to group into two regions of behavior with respect to the coning angle. For angles more negative than -10°, the pitch moment (M') is highly dependent upon rotation rate. However, for coning angles between 0 and -10° the shape of the M' surface is independent of ω'. Similarly, the sway force (Y') passes through a saddle at about -10°, at which point the nature of the surface changes direction, passing through zero again at about $\alpha_c = -15°$. The following sections describe a method of visualizing the flow near the model. The force and moment data lead to the conclusion that something transitional occurs near $\alpha_c = -10°$, and indeed it will be shown that the body-shed vortices first become visible over the model length after $\alpha_c = -10°$.

Relationships between the experimental parameters α_c and ω and the measured hydrodynamic forces and moments do not tell the entire story of flow-induced motion response for the vehicle. The process described above has built an empirical body of evidence to derive dependencies. Translation of those relationships to a more practical basis of hydrodynamic performance as a function of roll rate and yaw rate sets the data up for inclusion into a larger group of experiments on more conventional captive model test facilities such as towing tank and radial arm tests. The experiments described herein lead to derivation of the partial derivatives with respect to angular velocities p and r.

Understanding the flow mechanisms which cause the resultant hydrodynamic forces is essential to advancement of the state of the art in hull design. The remainder of this report develops a method of measuring the velocity field near the manuevering vehicle so that numerical and graphical techniques may be used to evaluate and visualize the flow character. The nonplanar motion of the vehicle in coning motion is the steady action of a vehicle rolling during a flat turn from an initial condition of steady forward velocity. The component of flow across the vehicle induces vorticity in a manner analogous to flow over a cylinder. For sufficient cross flow, the body sheds two vortices from the separation points into the

surrounding flow. The longitudinal velocity carries the vorticity along the body, interacting with the locally shed vorticity distribution along the remaining length. The roll component of vehicle motion complicates analysis of the process and gives rise to other coupling because it leads to asymmetry of the vortices shed from the body. The two dimensional analogy of a rotating bluff body would result in a lift force and drag. The flow visualizations are expected to demonstrate the distribution of vorticity. Given the predicted transition near α_c = -10°, the flow should be significantly different for experiments at coning angles above and below -10°.

Chapter 5

Description of Test Apparatus for Flow Mapping

5.1 Model

The model used in flow mapping has the same basic geometry of the instrumented model. It is constructed without any sensor devices. It has the capacity to accept a fin appendage or a blanking plug in a receptacle located about eight inches aft of the bow. A special sting shaft was built to mate this model to the sector described earlier. The new sting had a slightly larger diameter at the end in the model, and a smooth transition to the diameter acceptable at the sector. If deflection of the shaft/model due to the effects of flow and rotation were to be considered, this distinction from the instrumented phase of testing may possibly be significant.

5.2 Laser Doppler Velocimeter

All of the laser doppler velocimetry equipment used herein is indigenous to the MIT Marine Hydrodynamic Laboratory. The system is based on a laser device which produces three separate and independently polarized beam pairs out of a prism (blue, green and violet). Two of the beam pairs are used in this project, and the third set is available for future work in three-component velocity measures. A very complete description of general systems and concepts used in laser doppler anemometry is found in reference [9]. Coney describes the MIT installation in reference [10].

Back-scattered light from particles suspended in the tunnel flow is collected by a photo-multiplier in each channel. The doppler shift in frequency of the scattered light compared to a reference beam is proportional to the velocity of the particle in the direction orthogonal to the polarization of the measuring laser beams. With two beam pairs, two of the three velocity components can be measured with respect to a coordinate system fixed in the laser/tunnel space. In this case, the measured velocities are the streamwise component u_o, and the vertical component w_o. The table on which the laser system is mounted allows controlled translation in the three directions corresponding to the (x_o, y_o, z_o) reference system. Computer controlled positioning of the table is used to automate the process of sampling a distribution of locations in the tunnel.

Figure 22 provides a diagram of the LDV equipment and laser beam schematic for one beam.

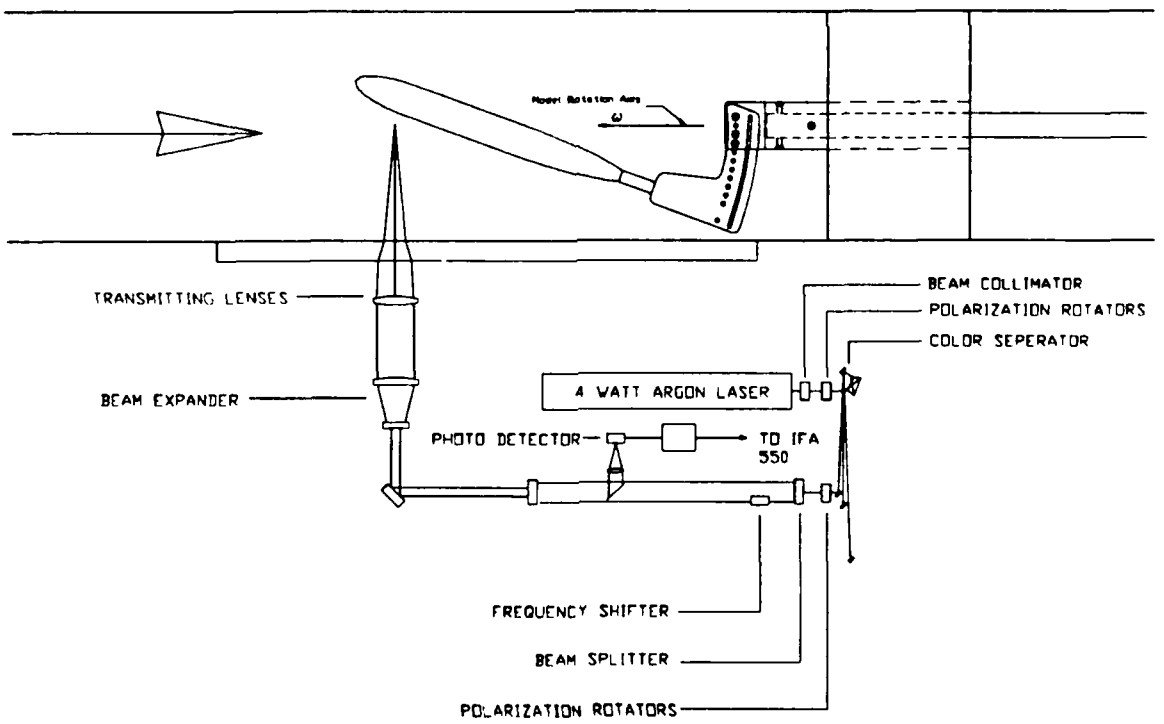


Figure 22: LDV Equipment Arrangement

5.3 Data Acquisition Systems

The data acquisition system for LDV experiments is based on an IBM compatible personal computer built by Everex which runs at 20 MHz using an Intel 80386 microprocessor. The PC operates software written by the author and by laboratory engineers to control the movement of the LDV through a controller which drives three independent stepping motors. The software provides closed-loop feedback control of LDV position referenced to magnetic position sensors. The same digital encoder described in chapter 2 is used to read angular position of the model about the spin axis, and its output is converted to a rotation rate display using a frequency counter. Figure 23 illustrates the data acquisition system schematically.

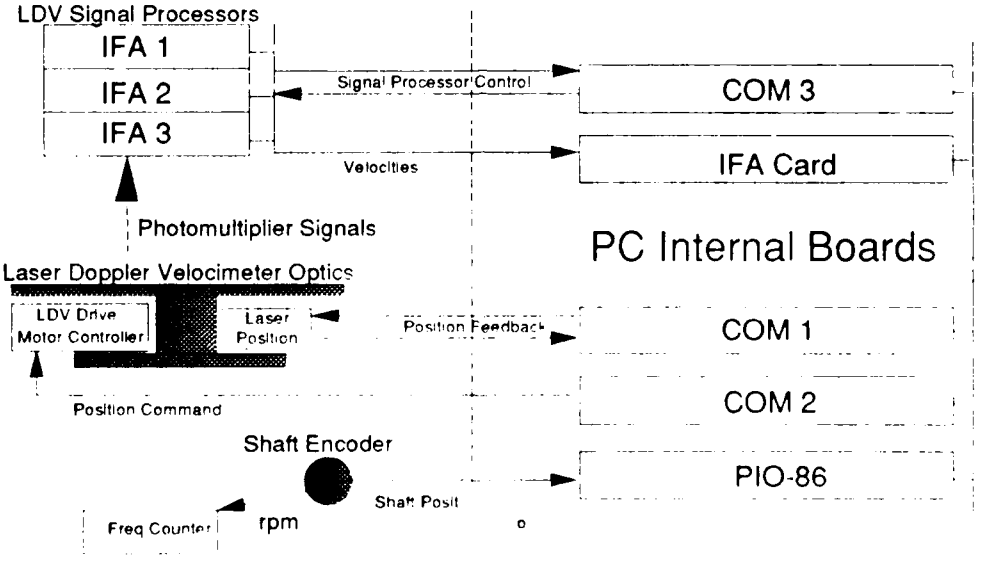


Figure 23: LDV Data Acquisition System

The PC surveys the output of the LDV system's Intelligent Flow Analyzers (IFAs) and matches velocity pairs with the angular position output of the encoder. Values are stored in data bins corresponding to angle (each is 2° wide, centered on even degrees). After collection of 4000 velocity/angle pairings, the LDV moves on to the next sample point in the water tunnel test section according to the operator's instructions

Chapter 6

Test Procedures for Flow Mapping

This chapter will present methods of obtaining and evaluating velocity data from the field surrounding the rotating body in coning motion.

6.1 Geometry of Laser Mapping

The goal in measuring flow velocities is to produce a view of perturbation velocities around the model cross-section at various longitudinal locations. The visualization of cross flow velocities at sections provides a step toward understanding the character and magnitude of vorticity shed due to the steady nonplanar cross flow of coning motion. The action of the resulting vortex sheets working along the hull and on each other accounts for complex nonlinear behavior in forces and moments.

In this work, the five stations in the tunnel where cross-sections were mapped were chosen to correspond to stations mapped in a series of static experiments conducted at MIT by Shields in 1988 [7]. The model used by Shields was the same model used in this project.

The laser doppler velocimeter (LDV) focuses its beams on a point in tunnel-fixed coordinates and takes data during the model's rotation. The set of data taken over a revolution forms a trajectory in body-fixed coordinate space. The shape of that trajectory must be determined to apply the data properly.

6.1.1 Transformation of Coordinates

The transformation of coordinates from stationary tunnel-fixed space to the rotating body-fixed reference frame may be described in the context of a rotation matrix. This matrix combines the independent effects of the model taking on a coning angle and moving to a rotational position with respect to the tunnel-fixed system. Derivation of the transformation for steady coning motion is given in Appendix A. Equations which relate the two frames of reference are:

$$x = x_o \cos\alpha_c + y_o \sin\alpha_c \sin\phi_o - z_o \sin\alpha_c \cos\phi_o \tag{5}$$

$$y = y_o \cos\phi_o + z_o \sin\phi_o \tag{6}$$

$$z = x_o \sin\alpha_c - y_o \cos\alpha_c \sin\phi_o + z_o \cos\alpha_c \cos\phi_o \tag{7}$$

Using this transformation, the path traced in body-fixed space by a tunnel-fixed sample point may be determined by parameterizing φ_o rotation. Given a coning angle and position in the tunnel (x_o, y_o, z_o), body rotation through one revolution translates to a sample point trajectory in (x, y, z) which lies in a plane orthogonal to a line rotated α_c from x in pitch. The trajectory is circular in that plane with radius $\sqrt{y_o^2 + z_o^2}$. The trajectory origin (center of the circle) is displaced from the x axis by $x_o \sin\alpha_c$. Figure 24 depicts this general path with respect to the model.

A series of laser sample points at a constant coning angle and x_o will fill the inclined plane with data points in circles of various diameters. This implies that for one location in space and one full rotation of the model in roll, a system which gathers velocities paired with roll angle may obtain several hundred data points at different locations in (x,y,z) space. By careful planning, the LDV data taking locations may be selected so that the velocities with respect to the body are measured optimally (i.e., without unnecessary redundancy).

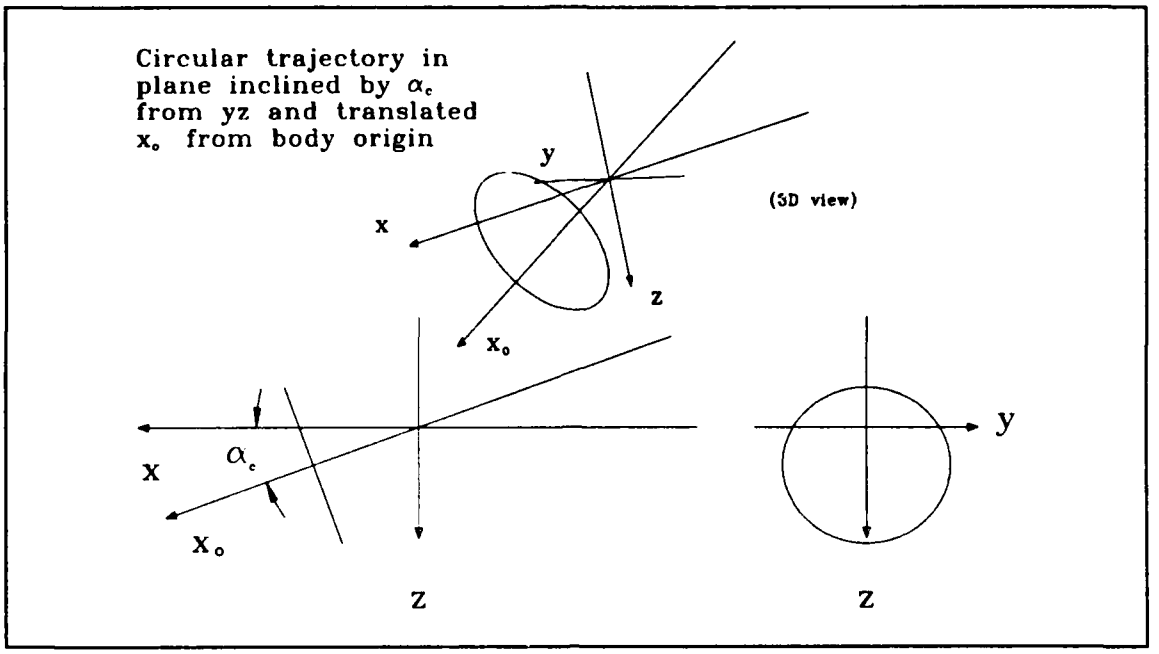


Figure 24: LDV Sample Point Trajectory

A useful presentation of this velocity data is a view of perturbation velocities in the body-fixed yz plane. The component of free stream velocity in the yz plane is the cross flow, $U_\infty \sin \alpha_c$. Perturbation velocities are determined by subtracting the magnitude $U_\infty \sin \alpha_c$ from the LDV measured vertical velocity in the yz plane.

For a fixed x_o series of tunnel cross section velocity measurements, the data vary in x location by $z \sin \alpha_c$. Therefore, near the body $x \approx x_o$ and at the tunnel walls $|x - x_o| \approx 10 \sin \alpha_c$ inches. Since the change in the u component of velocity changes so little with x, especially with increasing distance from the body, data are presented as if measured at fixed x. This assumption may be corrected by either changing the portrayal of perturbation velocities to the inclined plane of sample trajectories, or by taking data at very large numbers of points in the tunnel (i.e., at a tight distribution of x_o so that a "slice" through the data is actually at a single value of x). The first solution complicates the visualization (because the views are not parallel to ship sections), and the second implies prohibitively large experiments for this developmental stage of the process.

The LDV system measures two velocity components with respect to the tunnel, u_o and w_o. As discussed in Appendix A, the relationship between velocities relative to the body and tunnel referenced velocities is expressed by

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{bmatrix} \cos\alpha_c & \sin\alpha_c \sin\phi_o & -\sin\alpha_c \cos\phi_o \\ 0 & \cos\phi_o & \sin\phi_o \\ \sin\alpha_c & -\cos\alpha_c \sin\phi_o & \cos\alpha_c \cos\phi_o \end{bmatrix} \begin{pmatrix} u_o \\ v_o \\ w_o \end{pmatrix} \tag{8}$$

The velocities u, v and w are not fully determined by u_o, w_o, α_c and φ_o except for certain values of φ_o. In the case where $\varphi_o = 0°$ or $180°$,

$$u = u_o \cos\alpha_c \mp w_o \sin\alpha_c \tag{9}$$

$$w = u_o \sin\alpha_c \pm w_o \cos\alpha_c \tag{10}$$

and v is undetermined. When $\varphi_o = 90°$ or $270°$,

$$v = \pm w_o \tag{11}$$

and u and w are undetermined. These equations can be used to find u and w for two different points in (x,y,z) when $\varphi_o = 0°$ and $180°$. We can find the v velocity component for those points by moving to a spot in (x_o,y_o,z_o) which is 90° rotated in y_oz_o from the original spot and using the measured velocity data for $\varphi_o = 90°$ and $270°$. By moving the LDV focus to two different spots and using data corresponding to a total of four roll positions, complete sets of velocities relative to the body (u,v,w) are obtained while measuring only u_o and v_o.

This idea that every point in (x,y,z) can be evaluated completely by measuring only two components with the LDV while keeping track of roll about x_o is the basis for the logic employed in this part of the experiment. It can be shown that if we take data at a series of points along $y_o = 0$ then the combination of $(u_o,w_o,\varphi_o)_{y=0}$ represents velocity normal to the trajectory in yz which was described above. Similarly, data taken along $z_o = 0$ and shifted in roll phase as $(u_o,w_o,\varphi_o\text{-}90°)_{z=0}$ represents velocity tangent to the trajectory in yz. As long as the sample intervals on each leg correspond to the other, the points will map one-to-one

in (x,y,z). Furthermore, because each sample point in (x_o,y_o,z_o) correlates to a complete trajectory in (x,y,z), we need only take data along the lines described in one quarter space of the tunnel (at a chosen x_o) as $z_o < 0|_{y_o=0}$ and $y_o < 0|_{z_o=0}$. The points in (x,y,z) which result from this scheme are distributed evenly along circles inclined from yz by α_c and concentric about $(x_o \cos\alpha_c, 0, x_o \sin\alpha_c)$.

6.1.2 Laser Relocation Instructions

A Fortran program to develop the sequence of sample points along the y_o and z_o axes was used to create the Laser Movement file according to data density parameters entered by the user. The u_o, w_o velocity data collected over a range of roll angles at each of these points in the y_oz_o half plane will map into complete velocity description in (u,v,w) at points distributed throughout the yz plane.

6.2 Data Gathering Process

The velocity data gathering software uses subroutines developed in the MIT Marine Hydrodynamics Laboratory to move the LDV focus to each point in the Laser Movement file of coordinates, and to measure u_o and w_o and pair the velocities with φ_o. Velocity measurements are grouped into bins corresponding to roll angles. Each of the 180 bins is two degrees wide and centered on even angles. At each location, the velocity measurement loops until 4000 data points are received and distributed within the bins. The computer may be configured to pause and provide the user with graphs representing the distribution of numbers of data points, magnitudes of velocities with respect to φ_o, and a summary of standard deviation from the mean within each bin. The user is afforded the choice of proceeding to the next point or lingering to gain more data in 4000 point increments. During development, the value of 4000 points was chosen to minimize the variance in number of

points within each bin, ensuring comparable statistical consistency over the full range of rotation angle positions. When a location is completed, the values written to the output file are the average velocities in each bin for u_o and w_o. The standard deviation within each bin was about 0.7 ft/sec in the u_o component (mean near 25 ft/sec), and about 0.3 ft/sec in the w_o component (mean near 0 ft/sec). The LDV is then repositioned to the next grid coordinates, and the process continues.

The end product in this raw data gathering phase is a file which lists u_o, w_o and φ_o for 180 even values of φ_o at each of the sample points along the negative tunnel-fixed axes. The data from this file will be transformed in the data reduction phase to describe completely the velocity in the body-fixed system at hundreds of unique points in (x,y,z). Those velocities may be represented further graphically, or used in numerical calculation of vortex strength distributions. An example of the output in each of its forms is included in Appendix C.

Chapter 7

Test Results: Flow Field Mapping

7.1 Data Reduction

The data are translated from u_o, w_o, and φ_o pairings at the LDV sample locations to u, v, and w at points in body-fixed space by employing equations presented in Appendix A. Equations (5), (6) and (7) of section 6.1.1 provide spatial translation for the $y_o=0$ data, and a check for $z_o=0$ data evaluated at φ_o-90°. Equation (30) of Appendix A relates the velocity components between systems and is repeated here:

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{bmatrix} \cos\alpha_c & -\sin\alpha_c\cos\phi_o & -\sin\alpha_c\sin\phi_o \\ 0 & \sin\phi_o & -\cos\phi_o \\ \sin\alpha_c & \cos\alpha_c\cos\phi_o & \cos\alpha_c\sin\phi_o \end{bmatrix} \begin{pmatrix} u_o \\ w_{o(y_o=0,\phi_o)} \\ w_{o(z_o=0,\phi_o-90°)} \end{pmatrix} \tag{12}$$

Cross flow components are changed to perturbation velocities by subtracting the ambient cross flow from the vertical direction relative to the body:

$$v' = v \tag{13}$$

$$w' = w - U_\infty \sin\alpha_c \tag{14}$$

The resulting data file for the body-fixed coordinate system has three velocity components (u,v,w) related to each point (x,y,z) on the various trajectories described previously. A final Fortran program to generate graphical images of cross flow in a yz section takes this body-fixed data as input. The output is a file written in Adobe PostScript which will drive most laser printers. The format of the image is a distribution of vectors whose lengths and directions correspond to the measured perturbation velocities in the sectional plane. A summary copy of a sample PostScript file is included in Appendix C.

7.2 Results

The LDV testing for this report was conducted to demonstrate feasibility of the technique for future work which may cover the wide, multidimensional spectrum of operating points which are possible in the MIT Coning Motion Apparatus. The test data reported in chapter 4 showed that heave force and pitch moment were much less dependent on rotation rate when coning angle was less than -10°. It seemed likely that formation of vorticity shed from the body was occuring near that coning angle (for constant free stream tunnel flow) so the LDV experiments included one angle below the breakpoint, -8°. The first LDV experiment was done at the extreme coning angle, -20° at a mid-range rotation rate of 75 rpm. As in the force and moment experiments, the tunnel velocity was maintained at 25 feet per second.

The next several pages provide cross-sectional views, in body-fixed coordinates, of the net perturbation velocities projected onto the plane of the body cross-section. Each view is for data at a specific longitudinal tunnel position relative to the center of rotation, measured in millimeters. The first three positions are for α_c=-20°, and at increasing distances aft of the COR. The first shows formation of two unequal body vortices. The next two demonstrate the shedding path into the surrounding fluid of the vortices as they are convected astern. In the second two views, however, a "shadow zone" obscures the starboard vortex. This shadow is a result of the body's obstruction of the LDV's laser beams during part of each rotation. A solution to the shadow problem is presented in the concluding chapter. Finally, the fourth view demonstrates the predicted lack of shed body vorticity at α_c=-8° due to the relatively small ambient cross flow.

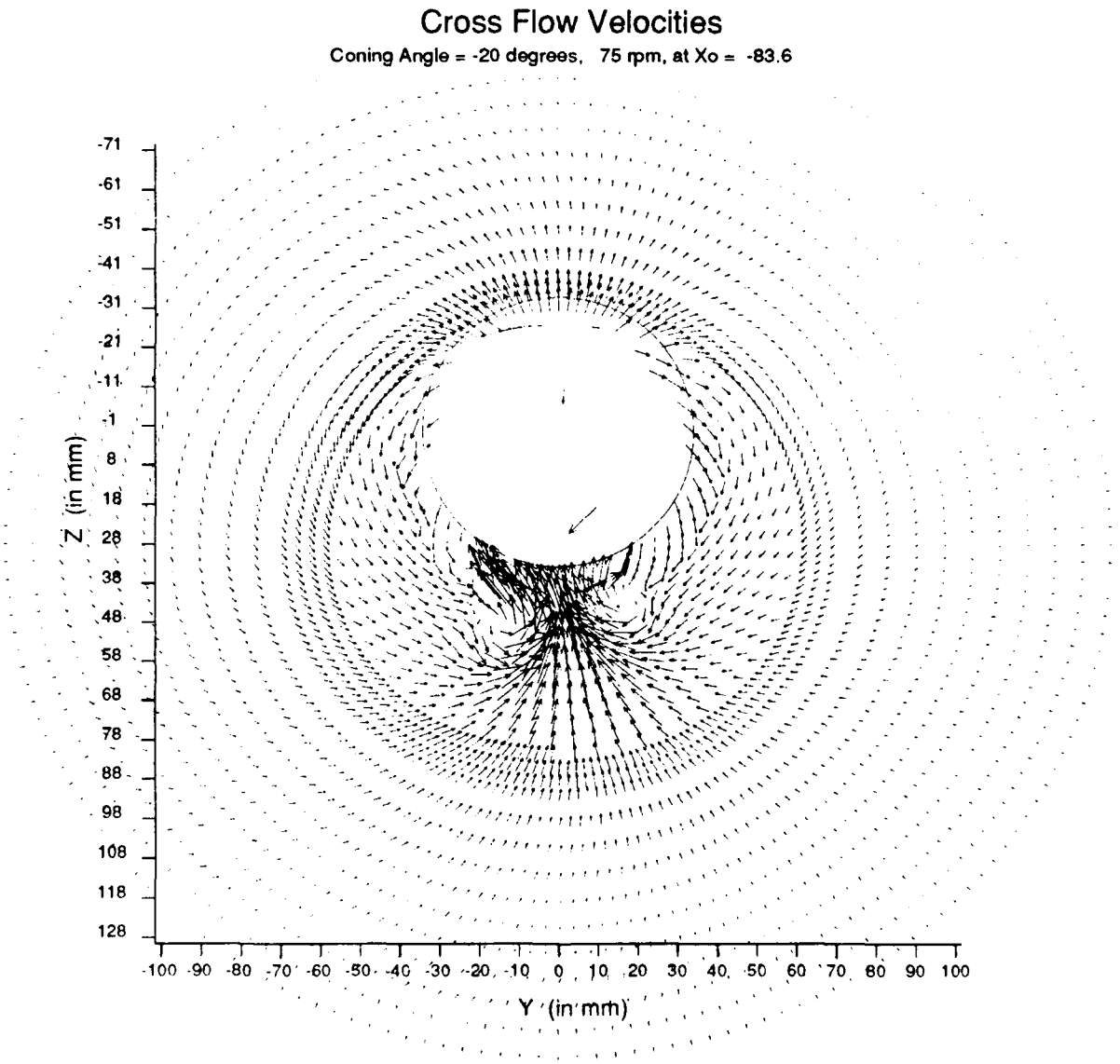


Figure 25: Perturbation Velocities at Section 3, α_c=-20°

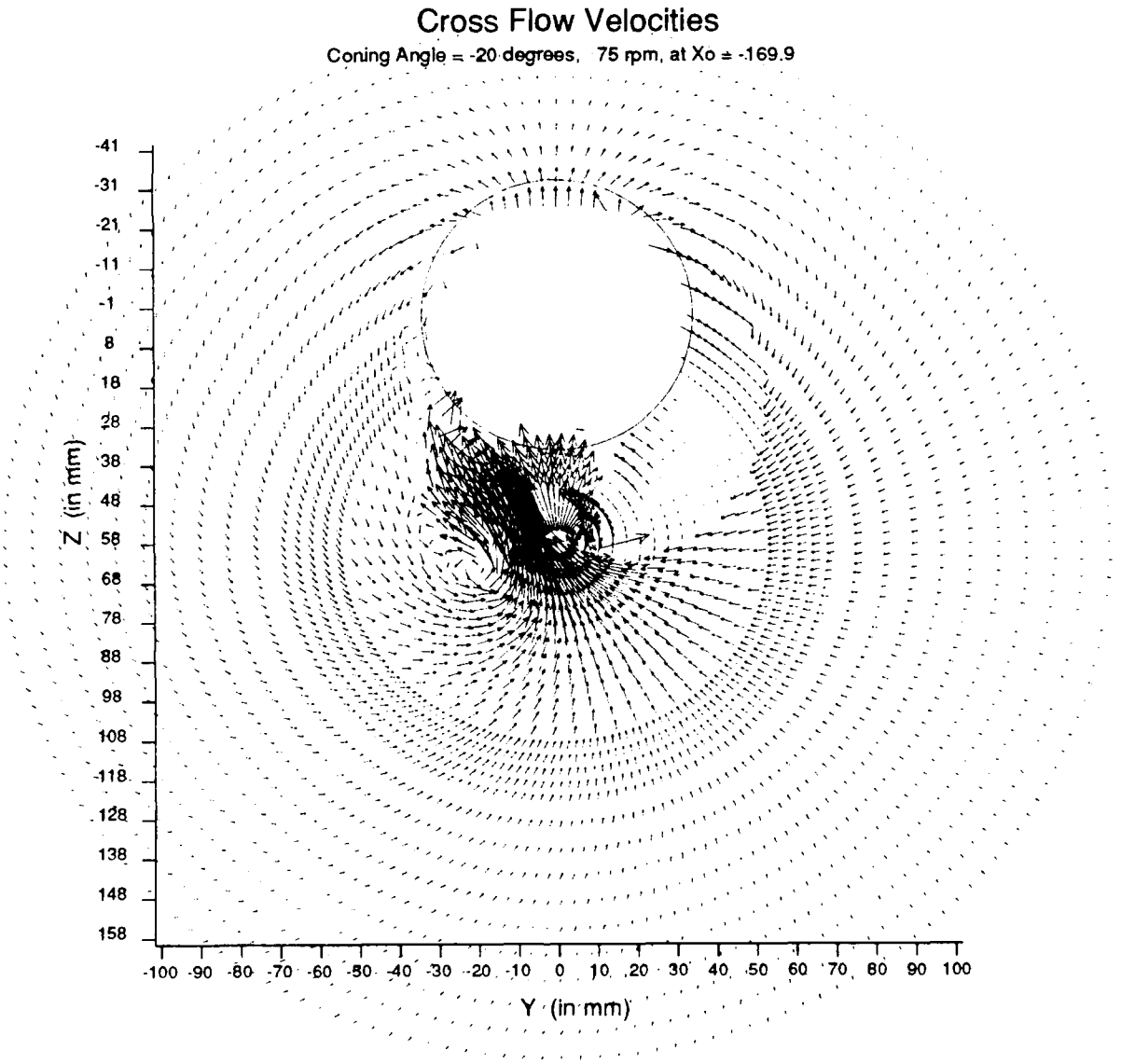


Figure 26: Perturbation Velocities at Section 4, α_r=-20°

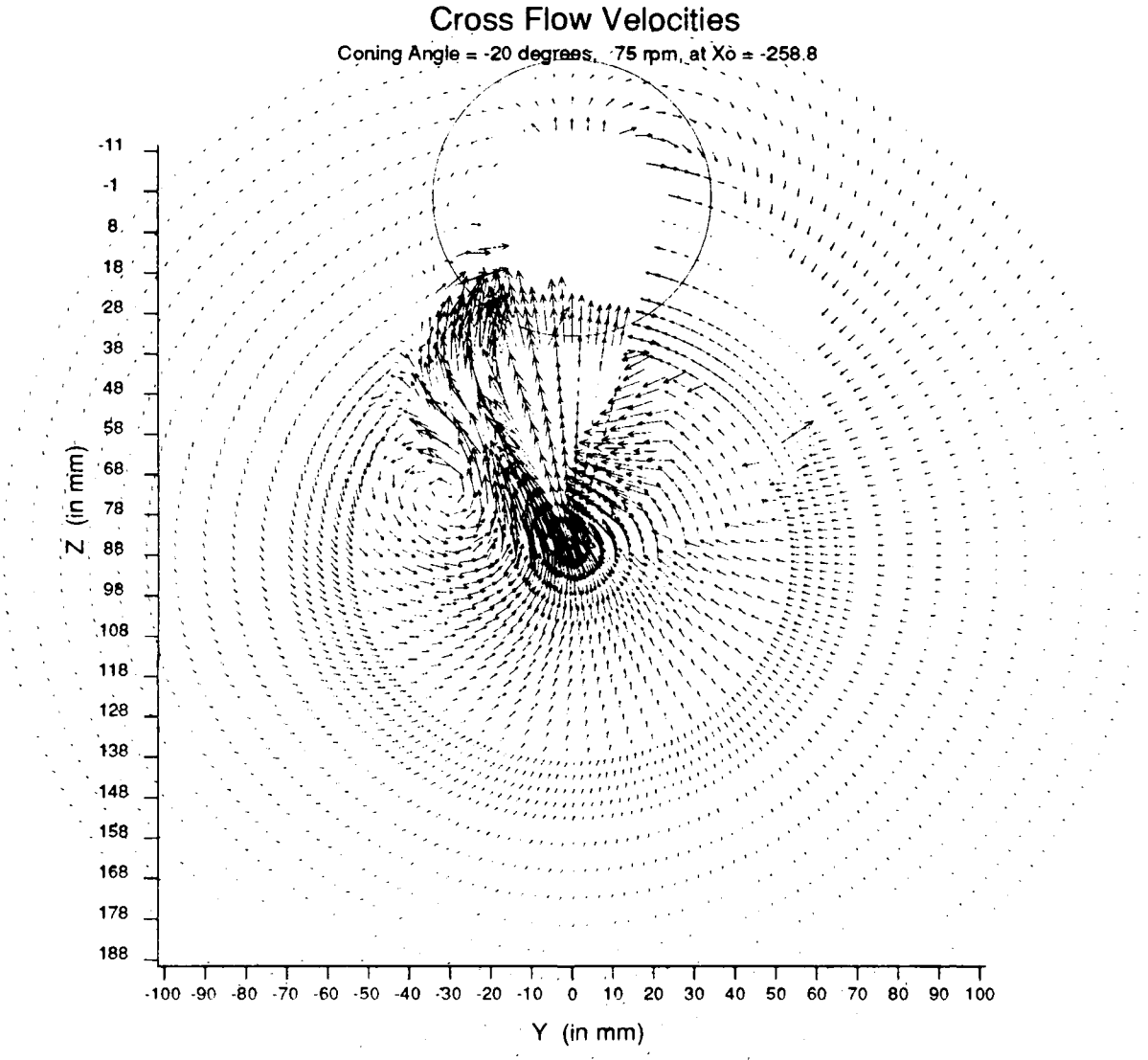


Figure 27: Perturbation Velocities at Section 5, α_c=-20°

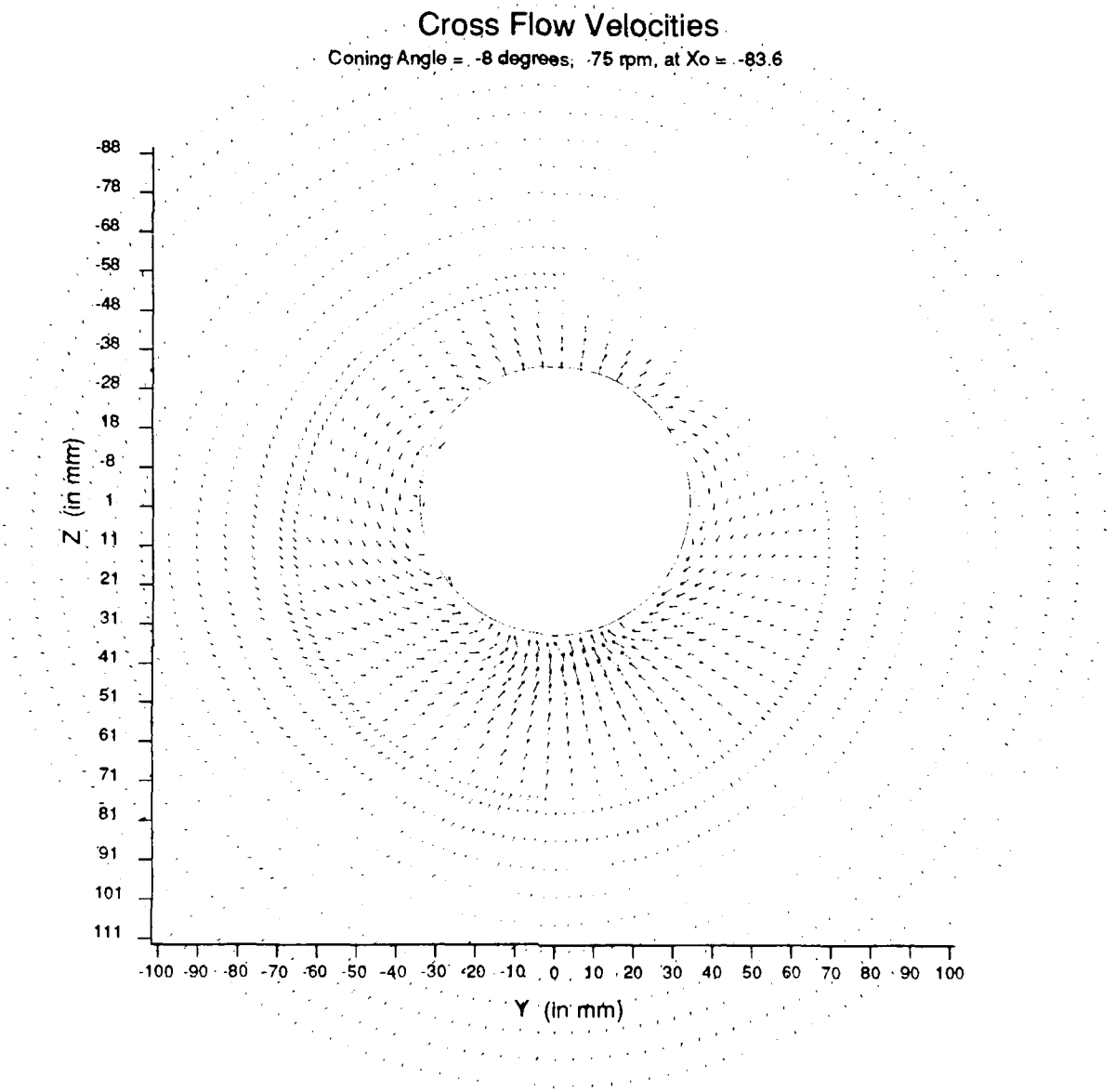


Figure 28: Perturbation Velocities at Section 3, α_s=-8°

Chapter 8

Conclusions and Recommendations

8.1 Conclusions

The goal in the coefficient measurement part of this project was the acquisition of a comprehensive set of force and moment data over a full range of coning angles and rotation rates. The goal was achieved by filling a matrix of over 350 experiments at different combinations of α_c and ω'.

The development of a method of flow visualization from a body-fixed perspective during steady coning motion was the second major goal of this work. The method was developed and demonstrated at two coning angles and one moderate rotation rate for five sections in the tunnel. A problem with partial data obscuration in regions where the model blocks the laser from its focal point was discovered at large coning angles and furthest longitudinal distances from the center of rotation. These "shadow zones", in the worst case, may obscure the important data associated with the body shed vorticity off one side of the model (see Figures 26 and 27 in chapter 7). A solution to the shadow problem is put forward in the next section.

The surfaces in (α_c,ω') space which define the dimensionless force and moment coefficients may be transformed using the relationship between α_c and ω' to describe the angular rotation rates experienced by the body given by equations (3). Partial derivatives with respect to roll rate and yaw rate may be measured from these transformed surfaces to yield some of the coefficients in series form equations of motion. The coupled nature of roll and yaw rates in coning motion provides a unique method of determining these

coefficients which is not offered by other conventional captive model test techniques. Actual surface fitting of this data and correlation with other sources (such as developmental analytical models) will be accomplished by the research sponsor.

8.1.1 Stability

For this report, a simplified analysis was conducted for positive rotation rates so that the dependence of forces and moments on roll rate and yaw rate could be determined in a linear model. The dimensionless data was transformed to correspond to the angular velocity variables of roll rate and yaw rate. By fitting the data to a fourth order polynomial using a least squares method, the partial derivatives at each operating point was evaluated.

The relationship between the measured forces and moments and the angular velocities (which describe the state of the system in the context of this set of experiments) may be represented by a nonlinear system matrix as

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} p' \\ q' \\ r' \end{bmatrix} \qquad \begin{bmatrix} K' \\ M' \\ N' \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} p' \\ q' \\ r' \end{bmatrix} \quad (15)$$

where the matrix coefficients are a function of the imposed velocity vector. An approximate method for assessing the stability of the hydrodynamic force and moment coefficients near the selected operating points is to evaluate the eigenvalues of a linearized form of the equations which describe the motion of small perturbations about a steady operating condition. These are the linearized form of equations (15) above. The components of the system matrices in a linearized problem become the first order partial differentials. The terms in p and r were found from the polynomial fit of the data. Since the coning motion evaluated here uses an unappended body of revolution, the terms describing dependence on

pitch rate may be assumed to be symmetric with the yaw rate terms. For this case then, the eigenvalues of the linearized systems of (X,Y,Z) and (K,M,N) were approximated over the ranges in p and r used in the experiments.

The partial differentials of X and K with respect to p and r are very nearly zero when compared with the magnitude of $\frac{\partial Z}{\partial r}$ and $\frac{\partial N}{\partial r}$. Also $\frac{\partial Z}{\partial p}$ and $\frac{\partial N}{\partial p}$ are small compared to the dominant term, so the two corresponding eigenvalues are real and nearly equal to zero. The other eigenvalue, which determines the nature of the unsteady response, is also real and is nearly equal to the term $Z_r = \frac{\partial Z}{\partial r}$ in the (X,Y,Z) system (and $N_r = \frac{\partial N}{\partial r}$ in the (K,M,N) system). Therefore, wherever Z_r has positive real part the system is not asymptotically stable in heave force for nonzero yaw rate. And similarly, for positive real parts in N_r the system is not stable in yaw moment.

Using the simplified linearized conclusions above and the results of a polynomial curve fit, the derivatives were calculated over the range of p and r. The curve fitting algorithm may be somewhat suspect because the coupled nature of the coning motion when projected into (p,r) space does not provide an evenly distributed set of data points. However, over most of the range of interest the error between equation and measured data was generally less than 10% and usually less than 3%. The derived partial slopes are as follows:

$Z_r \leq 0$ everywhere except along $r = 0$

$N_r \geq 0$ throughout the range in (p,r)

This rough analysis indicates that the heave force is asymptotically stable and the yaw moment is unstable for variation in the coupled angular velocities p and r. The interesting observations would come with more refined knowledge of the nonlinear dependences, but this "back of the envelope" look at stability may be a first step in evaluating the trends observed for sensitivity and maneuvering character.

8.1.2 Transition After α_c=-10°

In the results presented in chapter 4, a transition in the nature of the nonlinear dependence on α_c and ω' was seen at a coning angle between -8° and -10°. Figure 18 is particularly indicative of the occurrence of some distinct change in the character of the pitch moment coefficient M' near α_c=-10°. In this case, M' is independent of ω' for α_c less negative than -10°, but varies dramatically with ω' after -10°. A possible explanation for the variation is the development of significant vorticity shed into the free stream by the body. Also, from Figure 16, the sway force coefficient Y' changes the sign of its slope with respect to coning angle at about the same point. The effect is to generate a positive sway force for coning angles beyond -15°, where it had been negative between 0 and -15°.

If the formation of body shed vorticity is considered as the superposition of a distribution of two dimensional cross-flow vorticies shed from the bluff hull and transported longitudinally by the component of stream velocity parallel to the hull axis, then the formation of the expected pair of vortex sheets should occur at some particular velocity associated with a transitional Reynolds number. The component of stream velocity orthogonal to the body axis is $U_\infty sin\alpha_c$, so for constant tunnel flow rate the change in section velocity is due to variation in α_c. In the demonstration of flow visualization, the LDV data show formation of strong body shed vortices at α_c=-20° and no vortex sheets at α_c=-8°. Additional tests have shown the first formation of this vortex shedding at about α_c=-10°. Also, note that because nonzero roll rate acts to oppose development of one vorticity direction and adds to the other, we should expect the strengths and locations of the two shed vortex sheets to be asymmetric. As the views of perturbation velocities demonstrate, this was confirmed by experiment.

The sway force component of positive Y' which develops after α_c = -10° corresponds to the lift generated by the cross flow over the rolling hull (analogous to flow about a cylinder with circulation). For coning angles smaller than -10° the sway force coefficient is negative

due to the resultant of the lengthwise distribution of viscous drag from negative yawing. That seems to be consistent given that the wetted surface area of the model aft of the center of rotation is greater than the surface area forward of the COR. In other words, for coning angles between 0 and -10° the sway force is mainly the expected drag due to yaw. For coning angles exceeding about -10° the addition of (opposing) lift due to roll rate and cross flow must be considered, and the vorticity shed from the body is visible in a perturbation velocity graphic. This lift force dominates the yaw drag after about α_c = -15°. Figure 16 (and 51) shows this for the case of positive roll and negative yaw rates, and Figure 52 demonstrates the same trend for negative roll and positive yaw rates.

8.2 Recommendations

The method of flow visualization presented here is feasible, but for large coning angles and greater distances from the model's center of rotation the problem of data obscuration can prevent complete characterization of important elements of the flow such as a body vortex. The problem arises because while the laser focal point is located inside the "cone" of the body rotation there may be some time when the model obscures the laser beams by passing between the laser source and the intended focus. The efficient use of all data gathered during the model's rotation allows for a minimum number of assigned LDV focal positions. However, when a particular position is blocked over a range of rotation angle, the result is seen in the graphical output as zero velocity in either the radial or tangential component of vectors. The missing component data form a "shadow" near the model. An example of this shadow effect is found if one looks for the starboard body-shed vortex in Figures 26 and 27.

A solution for the shadow problem is achievable at the cost of adding several more LDV focal positions to the grid file and performing some overlaying of data within the post-processing software. The same information that one gathers by taking data along the

negative y_o and z_o axes may be obtained by looking at analogous positions on the positive legs of those axes and shifting the data by a phase difference in φ_o. By recognizing which points may be abscured during rotation, the experimenter may add the necessary duplicative points to "fill in the shadow" with valid, nonzero velocity measurements. The process of matching zero values with the repeat data may be undertaken in the program which transforms tunnel-fixed data to the body-fixed system. This is a reasonably simple series of comparisons and sorts which recognize inappropriate zero velocities and rewrite a value which corresponds to the same position in body-fixed space. The first effort to implement this solution is proceeding today at MIT's Marine Hydrodynamic Laboratory.

Further steps in this experimental program will naturally include using the laser doppler velocimetry techniques developed here to map the near-body flow over a range of parameters including coning angles, rotation rates and perhaps for varying tunnel velocities. The model may have a fin appendage added and, with slight modifications to the sting shaft, the model roll angle with respect to the rotating system may be changed from 0° to 90°. The addition of an appendage and change in roll angle would allow dynamic versions of the sort of flow experiments conducted at static positions by Shields in 1987 [7]. It is expected that coupling of the appendage-shed vorticity would be significant in its effect on body reactions.

The force and moment measurements conducted here will likely be expanded to include experiments with a fully instrumented fin appendage. Again, model roll angle might be varied to increase the number of experimental parameters.

Numerical analysis of flow velocity data may provide more quantitative insight into the complex vortical mechanisms working over the model length to influence ship motions. Such work might include determining the strength distribution of the vortices in three dimensions. Closer spacing of the sample sections would probably be required to obtain

sufficient detail. Comparison of these experiments with the patterns predicted by leading edge analytical tools would be useful in validating the computational methods of predicting vehicle motions.

References

1. Johnson, David C., "A Coning Motion Apparatus for Hydrodynamic Model Testing in a Non-Planar Cross-Flow", Master's Thesis, MIT, 1989.

2. "Nomenclature for Treating the Motion of a Submerged Body Through a Fluid," SNAME Technical and Research Bulletin No. 1-5, 1952.

3. Lewis, Edward V., editor, Principles of Naval Architecture (Second Revision), The Society of Naval Architects and Marine Engineers, Jersey City, New Jersey, 1989.

4. Abkowitz, Martin A., Stability and Motion Control of Ocean Vehicles, Massachusetts Institute of Technology, MIT Press, Cambridge, 1969.

5. Kaplan, J., "Velocity Measurements on a Body of Revolution with an Attached Fin", Master's Thesis, MIT, 1986.

6. Reed, J., "Measurement of Forces and Moments On, and Velocity About a Body of Revolution With an Attached Fin at Angles of Attack", Master's Thesis, MIT, 1987.

7. Shields, Lisa, "A Hydrodynamic Study of a Submerged Vehicle", Master's Thesis, MIT, 1988.

8. Mendenhall, M.R. and Perkins, S.C., Jr., "Nonlinear Hydrodynamic Analysis of Submarine Configurations", Nielsen Engineering and Research, Inc., NEAR TR-388, June 1988.

9. Durst, F., Melling, A., and Whitelaw, J.H., Principles and Practice of Laser-Doppler Anemometry, Academic Press Inc., London, 1981.

10. Coney, W.B., "Circulation Measurements on a Body of Revolution with an Attached Fin", Master's Thesis, MIT, 1985.

11. Crandall, S.H., Karnopp, D.C., Kurtz, E.F., Jr., Pridmore-Brown, D.C., Dynamics of Mechanical and Electromechanical Systems, Robert E. Krieger Publishing Company, Malabar, Florida, 1985.

12. Newman, J.N., Marine Hydrodynamics, MIT Press, Cambridge, 1977.

13. Lamb, Sir Horace, Hydrodynamics, Dover Publications, New York, 1945.

Appendix A

Coordinate Transformations in Rotating Systems

A.1 Positions

The problem of mapping data taken in a water tunnel/laser table based reference frame during model rotation to locations in a model fixed reference frame was solved by considering the superposition of independent motions to develop a rotation matrix, [C], which describes the following relationship

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = [C(\alpha_c, \phi_o)] \begin{pmatrix} x_o \\ y_o \\ z_o \end{pmatrix} \tag{16}$$

The coning motion may be constructed from a starting point where the tunnel and body coordinates are coincident by adding two independent motions. The first is to pitch the body to a coning angle α_c without roll. The second movement, which will be parameterized in time as a continuous steady motion, is to roll the (x,y,z) frame to an angle φ_o about the tunnel's x_o axis. Each movement may be represented by a separate rotation matrix as

$$\begin{pmatrix} x_{\alpha_c} \\ y_{\alpha_c} \\ z_{\alpha_c} \end{pmatrix} = [C_{\alpha_c}] \begin{pmatrix} x_o \\ y_o \\ z_o \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} x_{\phi_o} \\ y_{\phi_o} \\ z_{\phi_o} \end{pmatrix} = [C_{\phi_o}] \begin{pmatrix} x_o \\ y_o \\ z_o \end{pmatrix} \tag{17}$$

Superposition of the two motions is given by series multiplication of the rotation matrices, so that

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = [C(\alpha_c, \phi_o)] \begin{pmatrix} x_o \\ y_o \\ z_o \end{pmatrix} = [C_{\alpha_c}][C_{\phi_o}] \begin{pmatrix} x_o \\ y_o \\ z_o \end{pmatrix} \tag{18}$$

A general matrix $[C_\theta]$ which relates a coordinate system (x',y',z') to a base coordinate system (x,y,z) by a rotation of θ about an arbitrary axis $\overrightarrow{u_\theta}$ is given by reference [11].

$$[C_\theta] = \cos\theta \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} + (1-\cos\theta) \begin{bmatrix} l^2 & lm & \ln \\ lm & m^2 & mn \\ \ln & mn & n^2 \end{bmatrix} + \sin\theta \begin{bmatrix} 0 & n & -m \\ -n & 0 & l \\ m & -l & 0 \end{bmatrix} \tag{19}$$

where $$l = \overrightarrow{u_x} \cdot \overrightarrow{u_\theta} \qquad m = \overrightarrow{u_y} \cdot \overrightarrow{u_\theta} \qquad n = \overrightarrow{u_z} \cdot \overrightarrow{u_\theta} \tag{20}$$

For the case of pitching to a coning angle α_c, $\overrightarrow{u_\alpha} = \overrightarrow{u_y}$ so

$$l_\alpha = \overrightarrow{u_x} \cdot \overrightarrow{u_y} = 0 \qquad m_\alpha = \overrightarrow{u_y} \cdot \overrightarrow{u_y} = 1 \qquad n_\alpha = \overrightarrow{u_z} \cdot \overrightarrow{u_y} = 0 \tag{21}$$

thus

$$[C_{\alpha_c}] = \begin{bmatrix} \cos\alpha_c & 0 & -\sin\alpha_c \\ 0 & 1 & 0 \\ \sin\alpha_c & 0 & \cos\alpha_c \end{bmatrix} \tag{22}$$

Similarly,

$$[C_{\phi_o}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi_o & \sin\phi_o \\ 0 & -\sin\phi_o & \cos\phi_o \end{bmatrix} \tag{23}$$

The product of these two provides the solution

$$[C(\alpha_c, \phi_o)] = \begin{bmatrix} \cos\alpha_c & 0 & -\sin\alpha_c \\ 0 & 1 & 0 \\ \sin\alpha_c & 0 & \cos\alpha_c \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi_o & \sin\phi_o \\ 0 & -\sin\phi_o & \cos\phi_o \end{bmatrix} \tag{24}$$

$$[C(\alpha_c, \phi_o)] = \begin{bmatrix} \cos\alpha_c & \sin\alpha_c \sin\phi_o & -\sin\alpha_c \cos\phi_o \\ 0 & \cos\phi_o & \sin\phi_o \\ \sin\alpha_c & -\cos\alpha_c \sin\phi_o & \cos\alpha_c \cos\phi_o \end{bmatrix} \tag{25}$$

This matrix leads to the equations of Chapter 6.1.1 from

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{bmatrix} \cos\alpha_c & \sin\alpha_c \sin\phi_o & -\sin\alpha_c \cos\phi_o \\ 0 & \cos\phi_o & \sin\phi_o \\ \sin\alpha_c & -\cos\alpha_c \sin\phi_o & \cos\alpha_c \cos\phi_o \end{bmatrix} \begin{pmatrix} x_o \\ y_o \\ z_o \end{pmatrix} \tag{26}$$

Finally, a transformation from a known tunnel coordinate position (x_o,y_o,z_o) to a body fixed coordinate position (x,y,z) may be made through simple equations which depend upon coning angle and roll position (α_c,φ_o). To reverse the transformation (i.e., from body fixed to tunnel fixed), the inverse of the rotation matrix may be used as

$$\begin{pmatrix} x_o \\ y_o \\ z_o \end{pmatrix} = [C(\alpha_c, \phi_o)]^{-1} \begin{pmatrix} x \\ y \\ z \end{pmatrix} \tag{27}$$

Since the matrix $[C(\alpha_c,\varphi_o)]$ is orthogonal, its inverse is equivalent to its transpose. Therefore the transformation of coordinates may be given by the following table, which allows coordinate translation in either direction:

Table 3: Coordinate Transformations

	x_o	y_o	z_o
x	$\cos\alpha_c$	$\sin\alpha_c \sin\varphi_o$	$-\sin\alpha_c \cos\varphi_o$
y	0	$\cos\varphi_o$	$\sin\varphi_o$
z	$\sin\alpha_c$	$-\cos\alpha_c \sin\varphi_o$	$\cos\alpha_c \cos\varphi_o$

A.2 Velocities

Particle velocities (u,v,w) may be represented by vector positions in (x,y,z), so the translation of velocity vectors follows the same method described above for positions. The result is that

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{bmatrix} \cos\alpha_c & \sin\alpha_c \sin\phi_o & -\sin\alpha_c \cos\phi_o \\ 0 & \cos\phi_o & \sin\phi_o \\ \sin\alpha_c & -\cos\alpha_c \sin\phi_o & \cos\alpha_c \cos\phi_o \end{bmatrix} \begin{pmatrix} u_o \\ v_o \\ w_o \end{pmatrix} \tag{28}$$

Since the LDV equipment measures two of the three tunnel fixed velocities (u_o,w_o), but not v_o, the body velocities u, v, and w are not obviously fully determined for most values of φ_o. This is the subject of some discussion in Chapter 6.

Let us first consider the simplified case of α_c=0. Then vertical velocity data gathered along the LDV axis where y_o=*0* and z_o<*0* may be described as normal to the trajectory in (*x*,*y*,*z*). Similarly, vertical velocity data taken along z_o=*0* for y_o<*0* represents velocity tangent to the same trajectory at locations along the trajectory shifted by -90°. For this zero coning angle case the body fixed velocities can be found from the streamwise, normal and tangential velocities by:

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \sin\phi_o & -\cos\phi_o \\ 0 & \cos\phi_o & \sin\phi_o \end{bmatrix} \begin{pmatrix} u_o \\ w'_{o_{(y_o=0,\phi_o)}} \\ w'_{o_{(z_o=0,\phi_o-90°)}} \end{pmatrix} \tag{29}$$

This use of orthogonal data taking legs in the water tunnel coupled with the rotation of the body allows simple movement of the LDV while mapping the entire space around the model. The general case of nonzero coning angle may be determined by multiplying the square matrix in equation (29) by the direction cosines matrix for coning, $[C_\alpha]$ of equation (22). The resulting transformation of (u_o,w'_o,α_c,φ_o) data to (u,v,w') is:

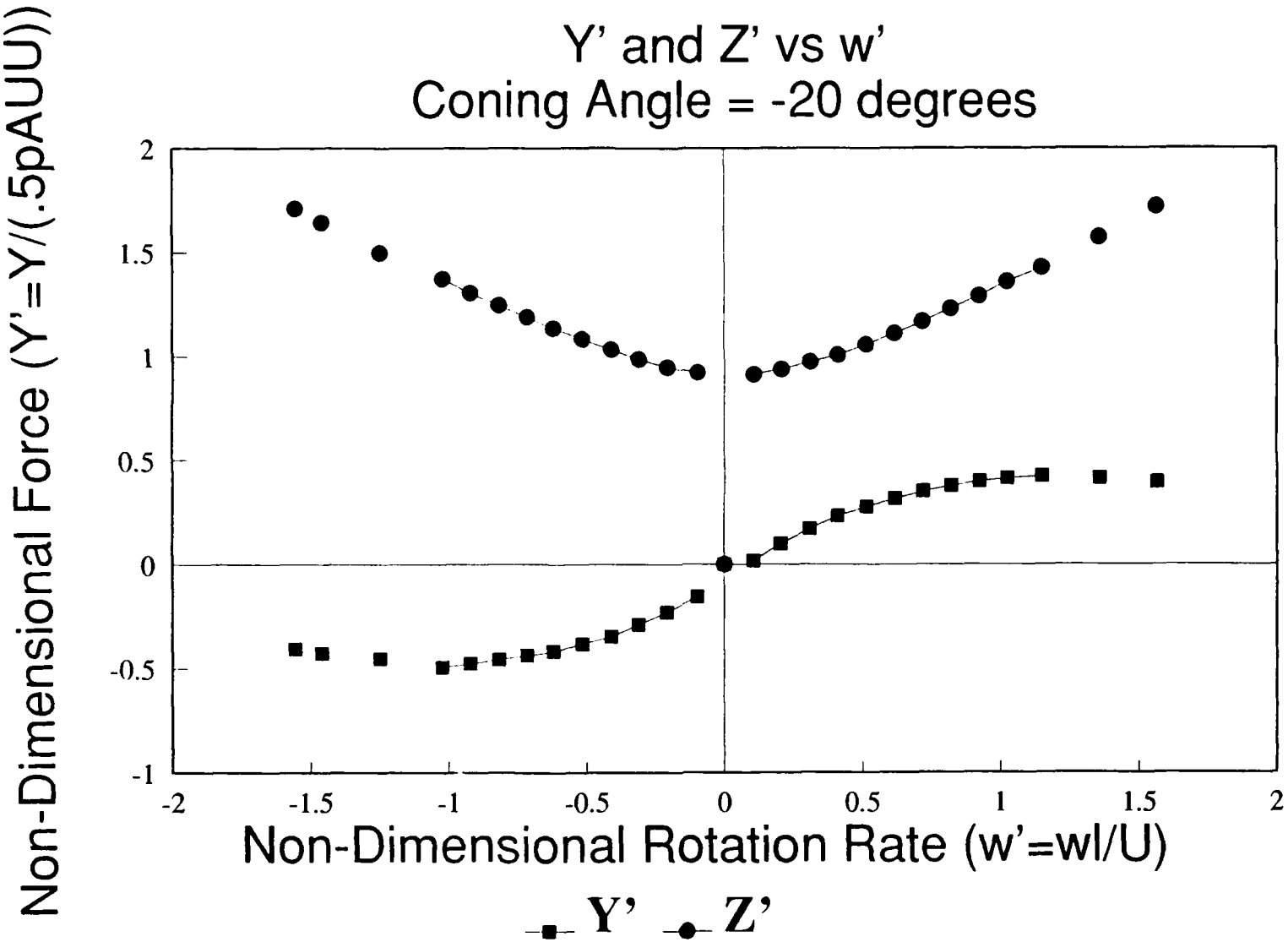
$$\begin{pmatrix} u \\ v \\ w' \end{pmatrix} = \begin{bmatrix} \cos\alpha_c & -\sin\alpha_c\cos\phi_o & -\sin\alpha_c\sin\phi_o \\ 0 & \sin\phi_o & -\cos\phi_o \\ \sin\alpha_c & \cos\alpha_c\cos\phi_o & \cos\alpha_c\sin\phi_o \end{bmatrix} \begin{pmatrix} u_o \\ w'_{o_{(y_o=0,\phi_o)}} \\ w'_{o_{(z_o=0,\phi_o-90°)}} \end{pmatrix} \tag{30}$$

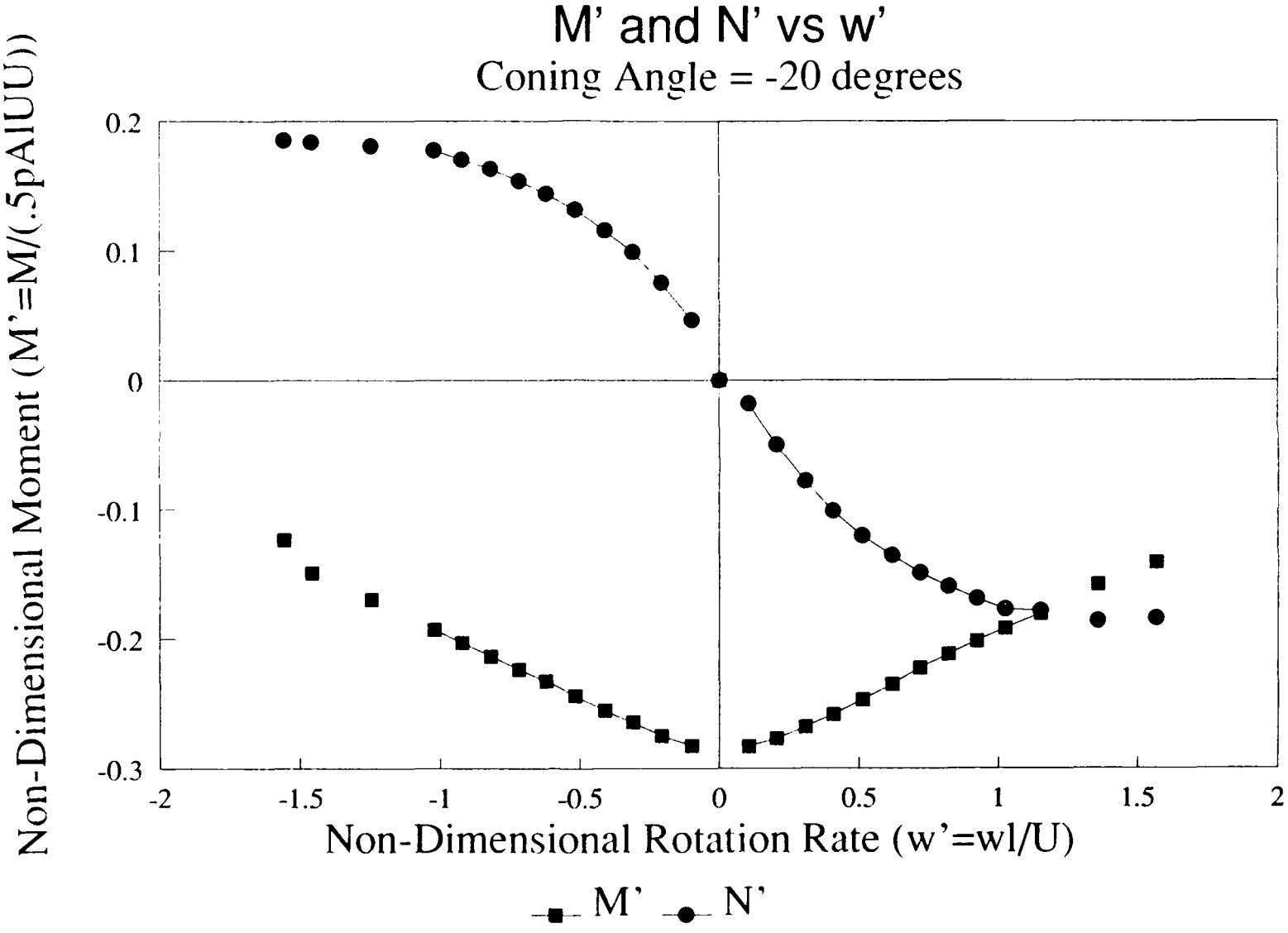
Appendix B

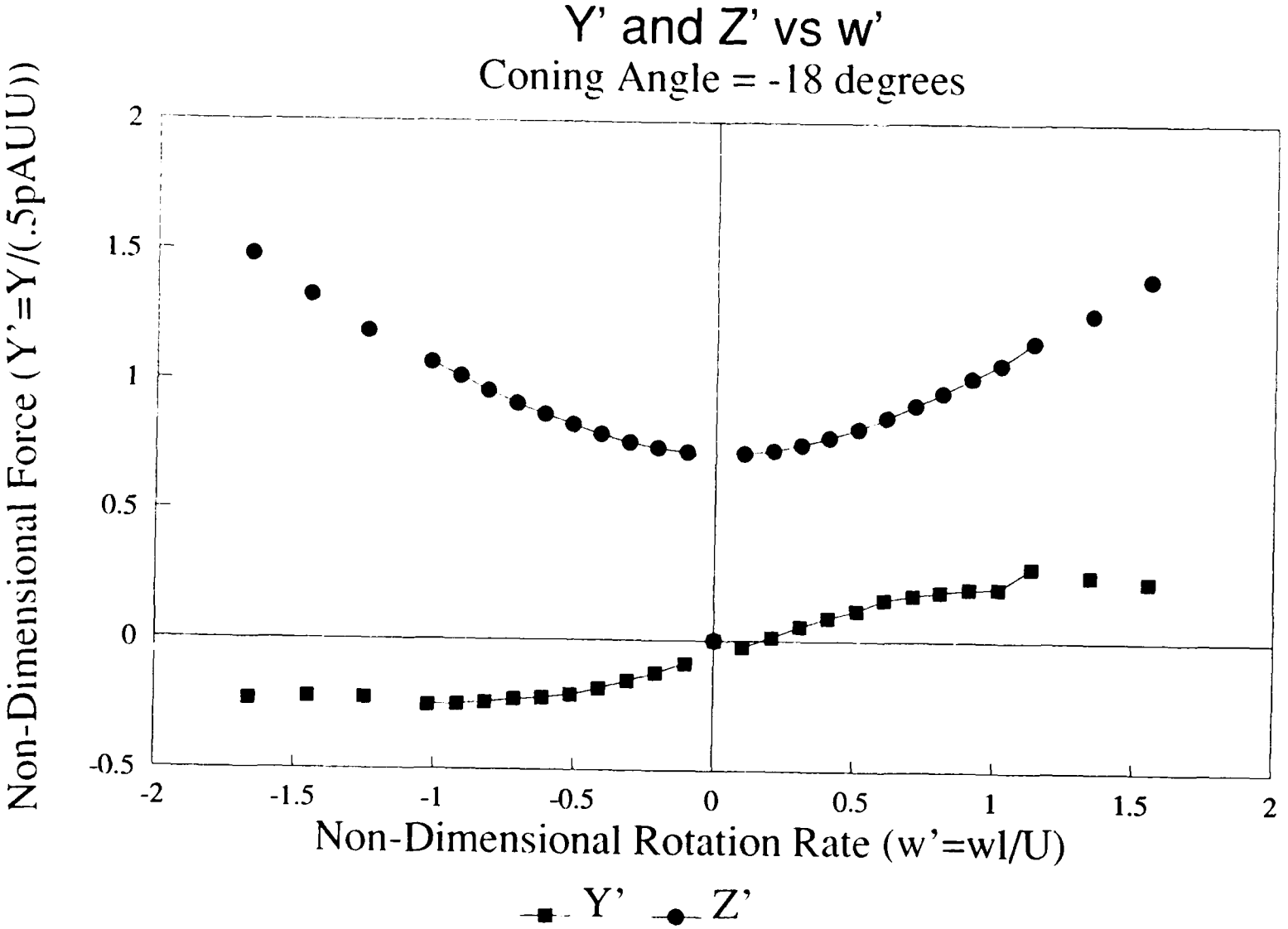
Test Data: Forces and Moments

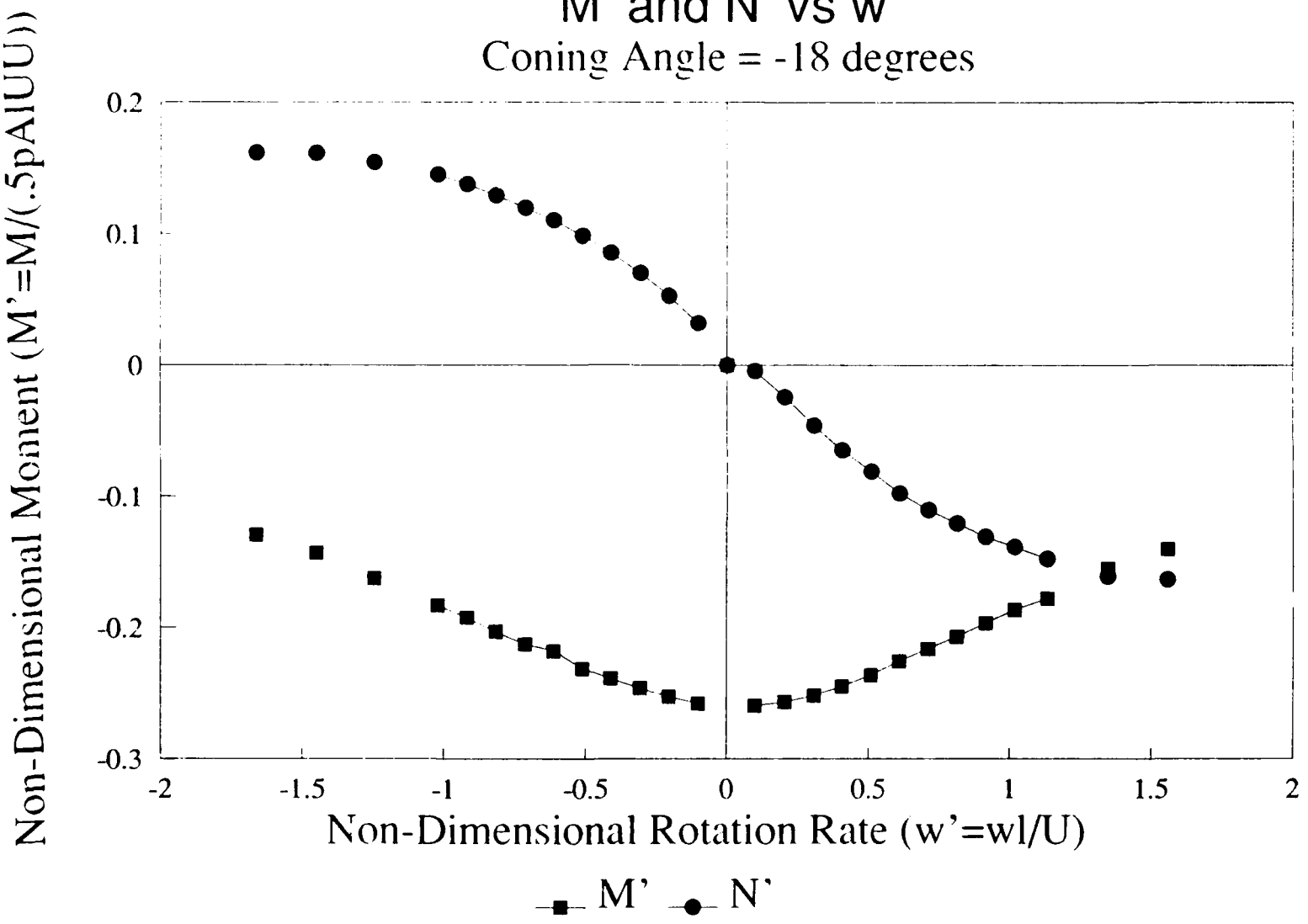
Data presented herein include:

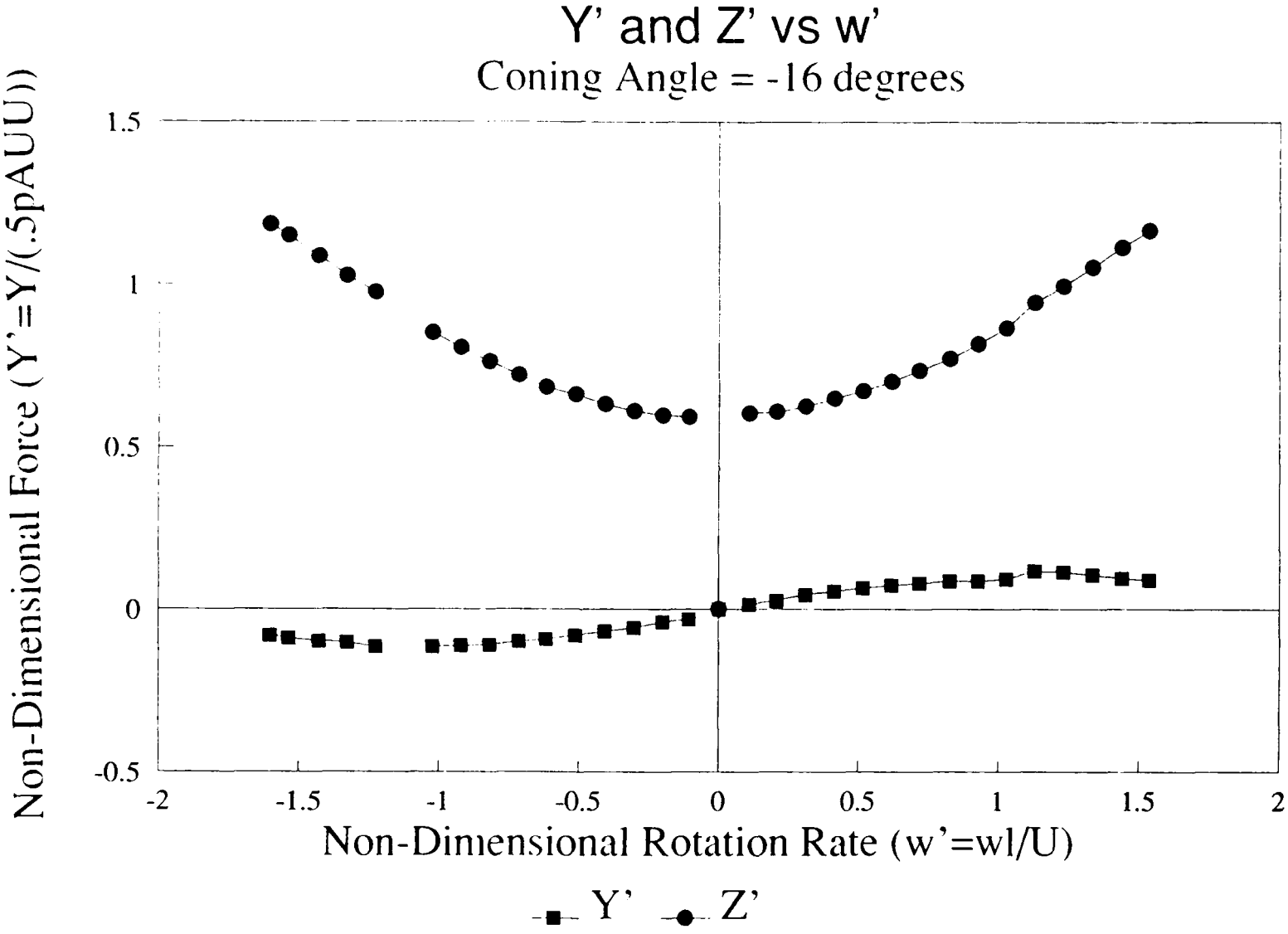
- Plots of Y′ and Z′ versus ω′ at each α_c
- Plots of M′ and N′ versus ω′ at each α_c
- Plots of Y′, Z′, M′, and N′ versus α_c for various rotation rates, both positive and negative
- Tabulated dimensionless force and moment coefficients for a range of ω′ at each $0° \leq \alpha_c \leq -20°$
- Identical data in units of pounds force and inch•pounds of moment for a range of rpm over the same coning angles

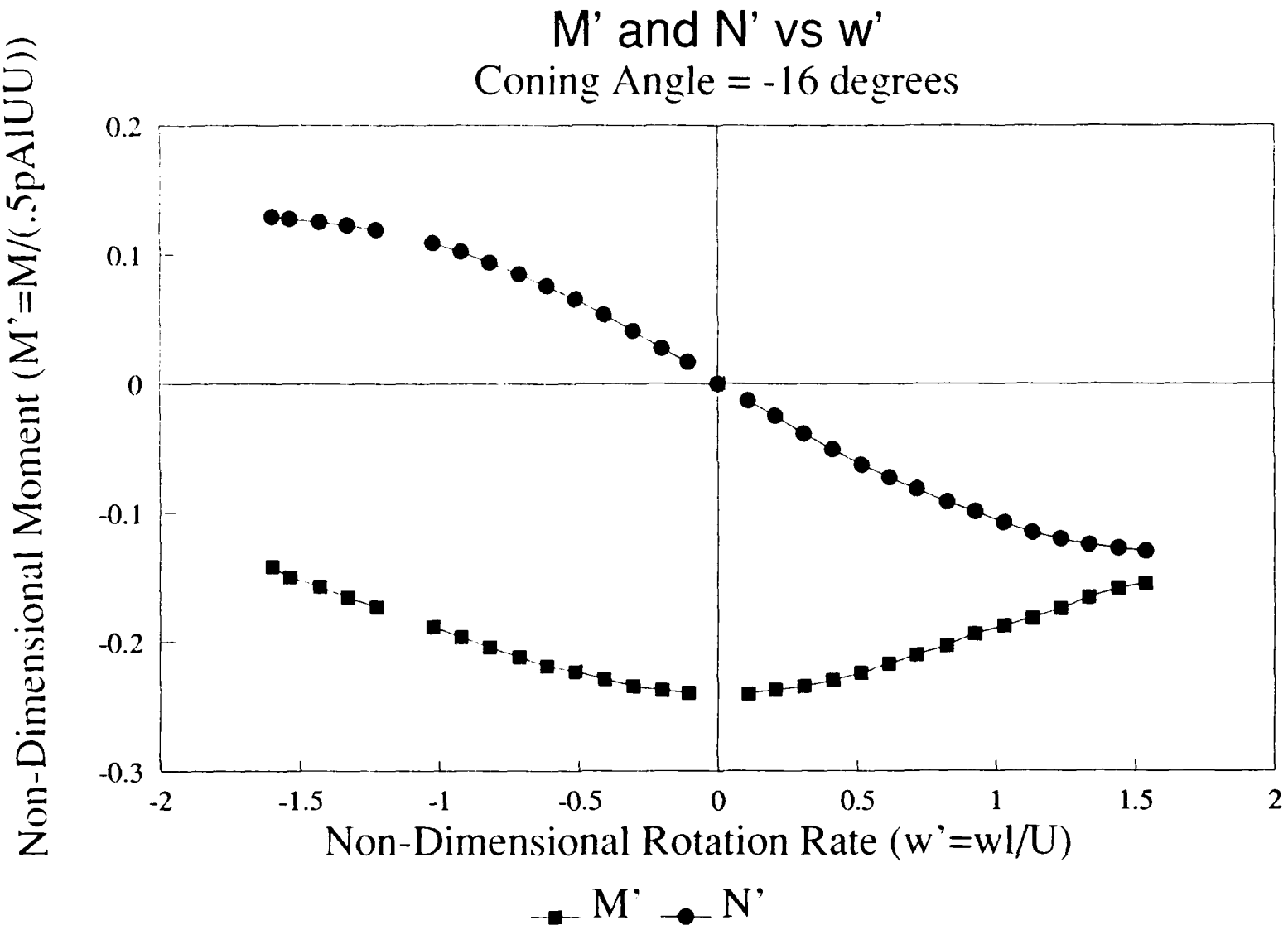

Y' and Z' vs w'
Coning Angle = -20 degrees
Non-Dimensional Force (Y'=Y/(.5pAUU))
2
1.5
1
0.5
0
-0.5
-1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
Y'
Z'

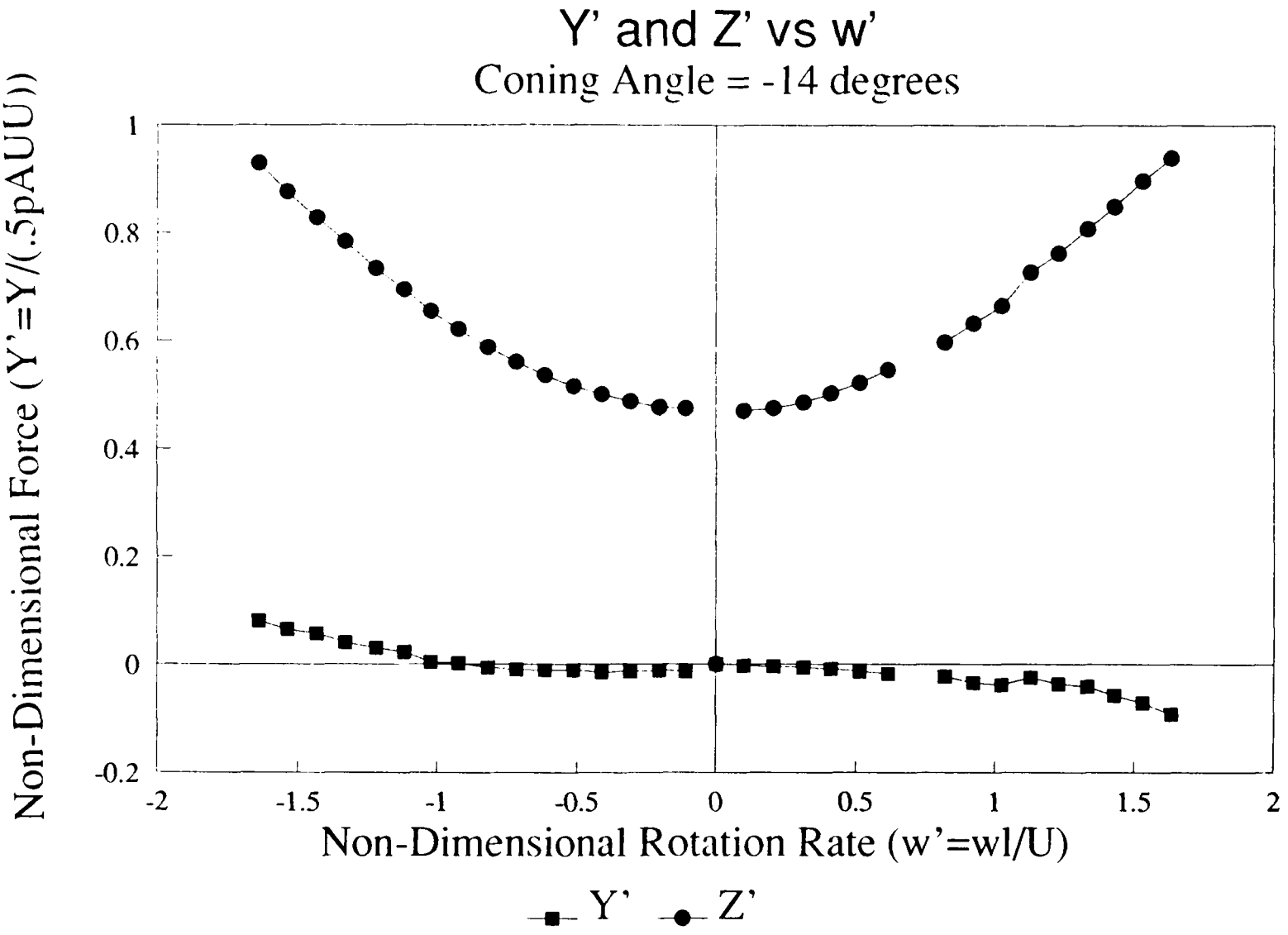

M' and N' vs w'
Coning Angle = -20 degrees
Non-Dimensional Moment (M'=M/(.5pAlUU))
0.2
0.1
0
-0.1
-0.2
-0.3
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
M'
N'

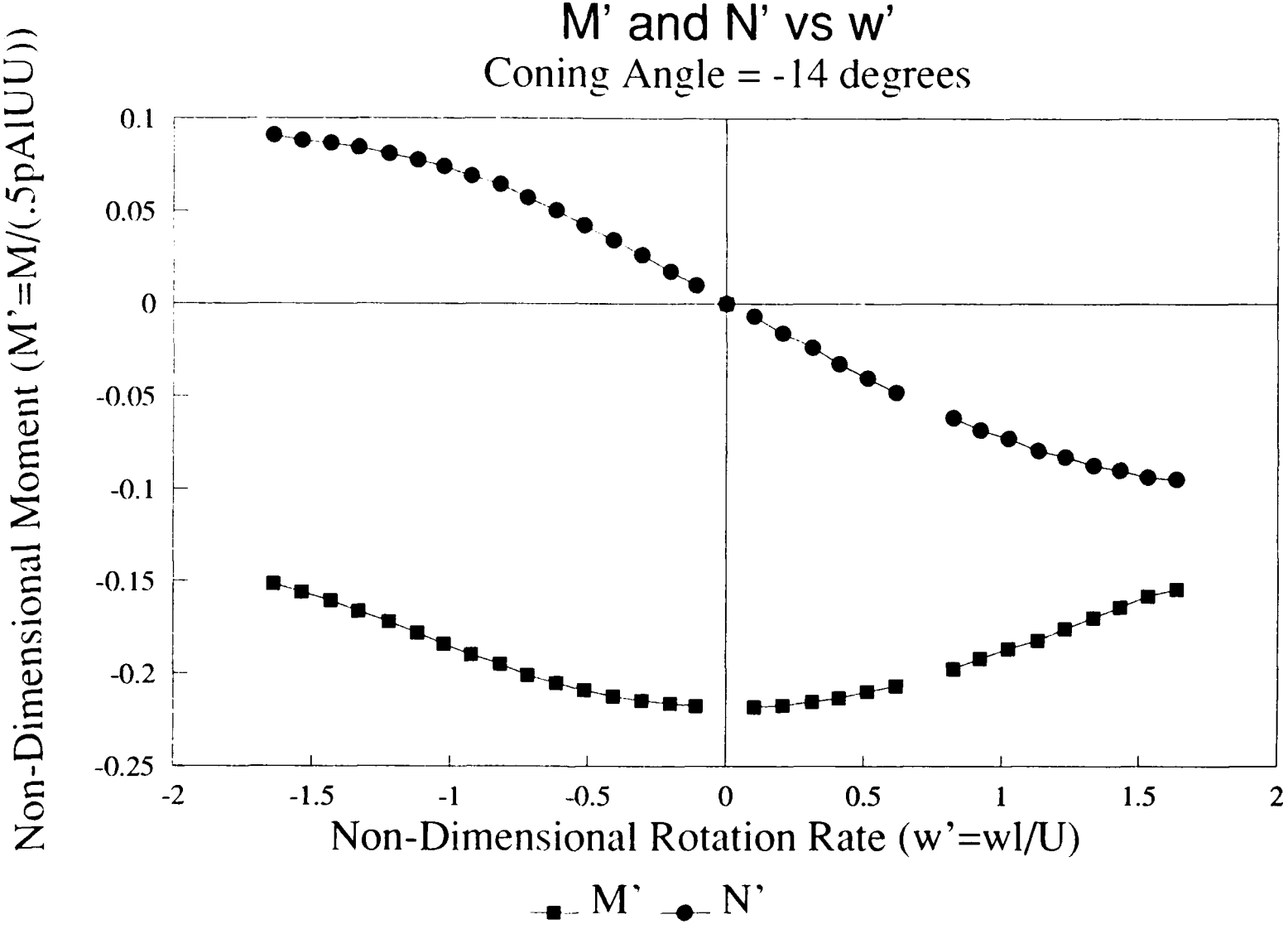

Y' and Z' vs w'
Coning Angle = -18 degrees
Non-Dimensional Force (Y'=Y/(.5pAUU))
2
1.5
1
0.5
0
-0.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
Y'
Z'

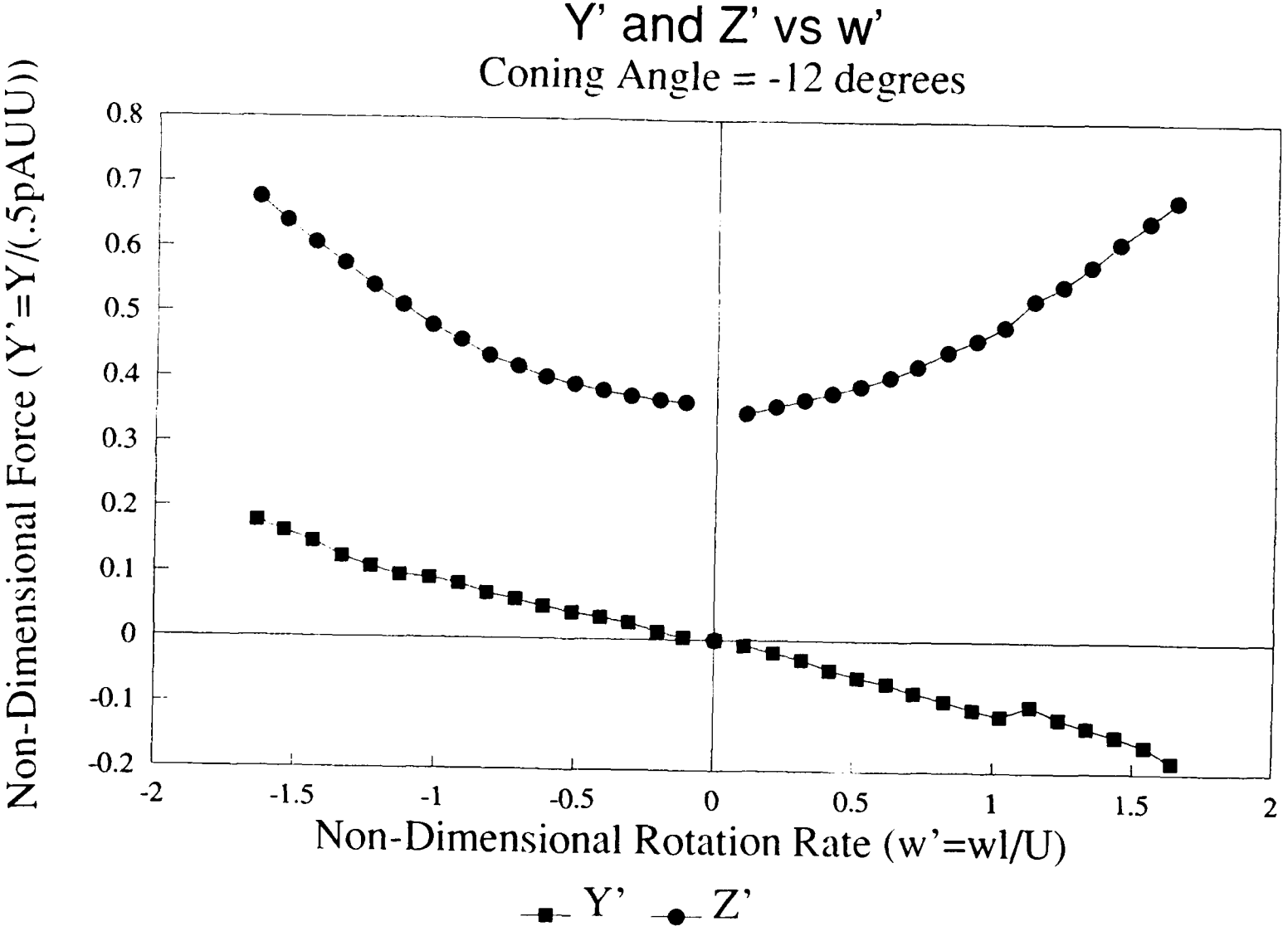

M' and N' vs w'
Coning Angle = -18 degrees
Non-Dimensional Moment (M'=M/(.5pAlUU))
0.2
0.1
0
-0.1
-0.2
-0.3
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
M'
N'

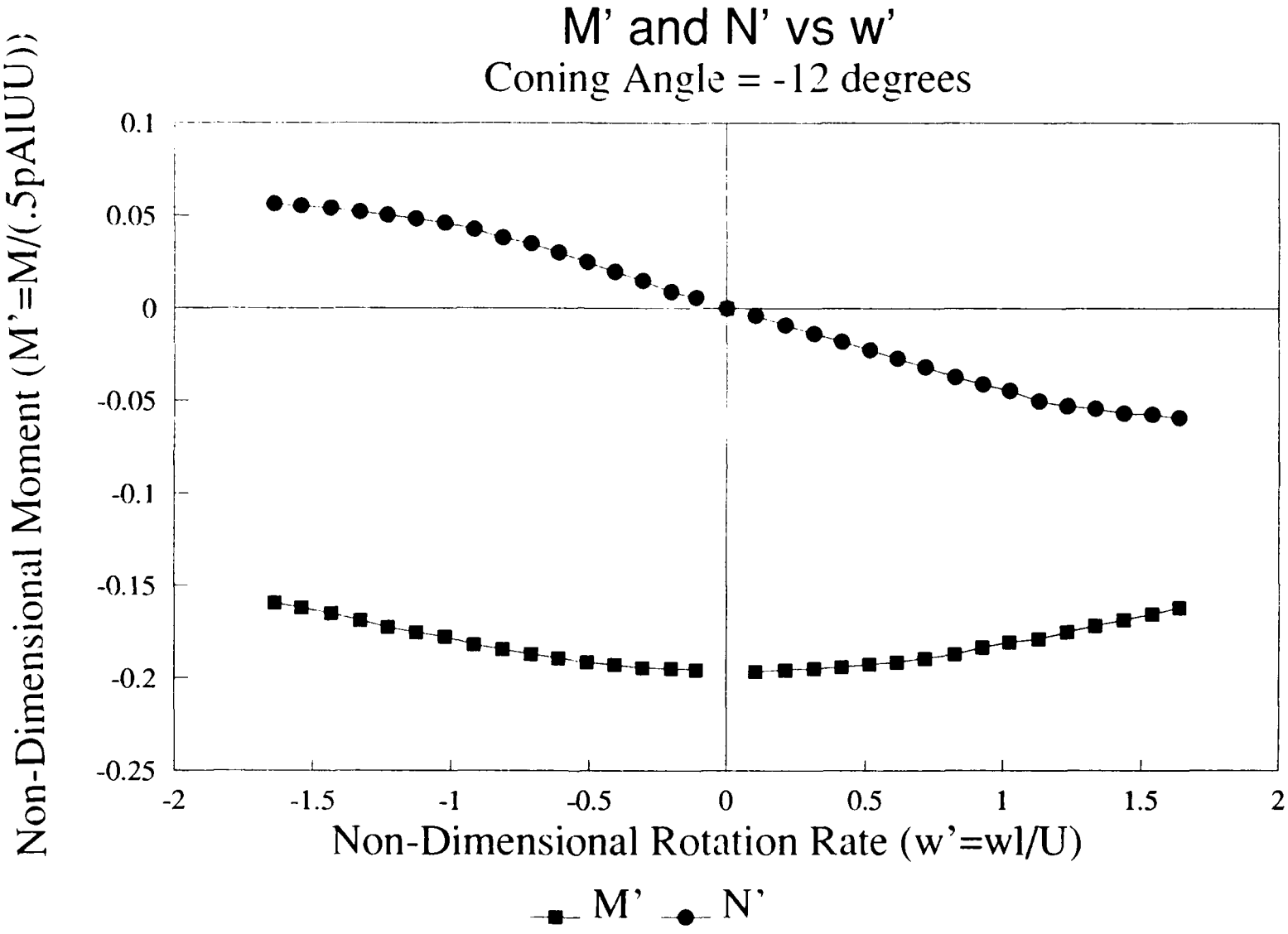

Y' and Z' vs w'
Coning Angle = -16 degrees
Non-Dimensional Force (Y'=Y/(.5pAUU))
1.5
1
0.5
0
-0.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
Y'
Z'

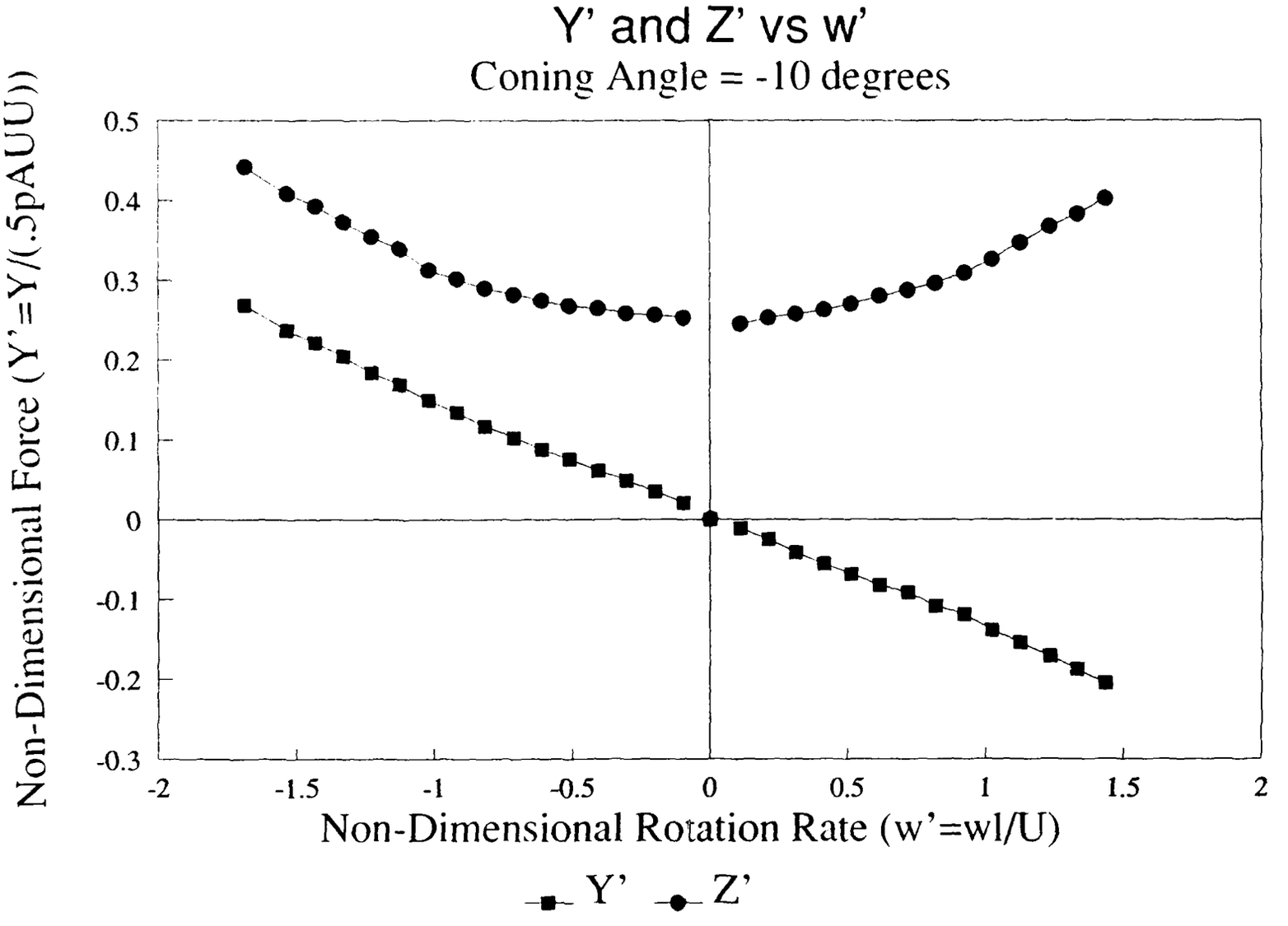

M' and N' vs w'
Coning Angle = -16 degrees
Non-Dimensional Moment (M'=M/(.5pAlUU))
0.2
0.1
0
-0.1
-0.2
-0.3
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
M'
N'

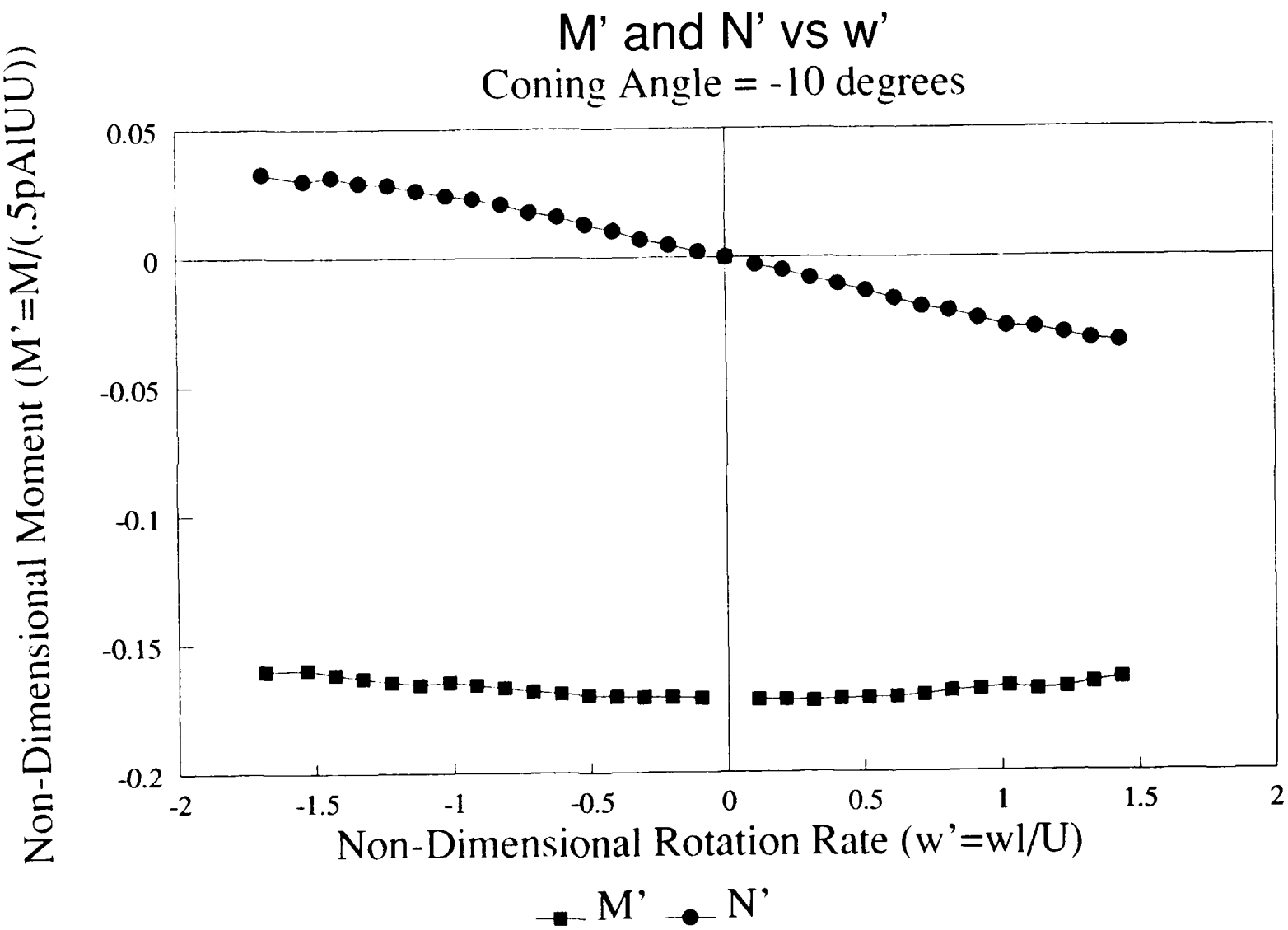

Y' and Z' vs w'
Coning Angle = -14 degrees
Non-Dimensional Force (Y'=Y/(.5pAUU))
1
0.8
0.6
0.4
0.2
0
-0.2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
Y'
Z'

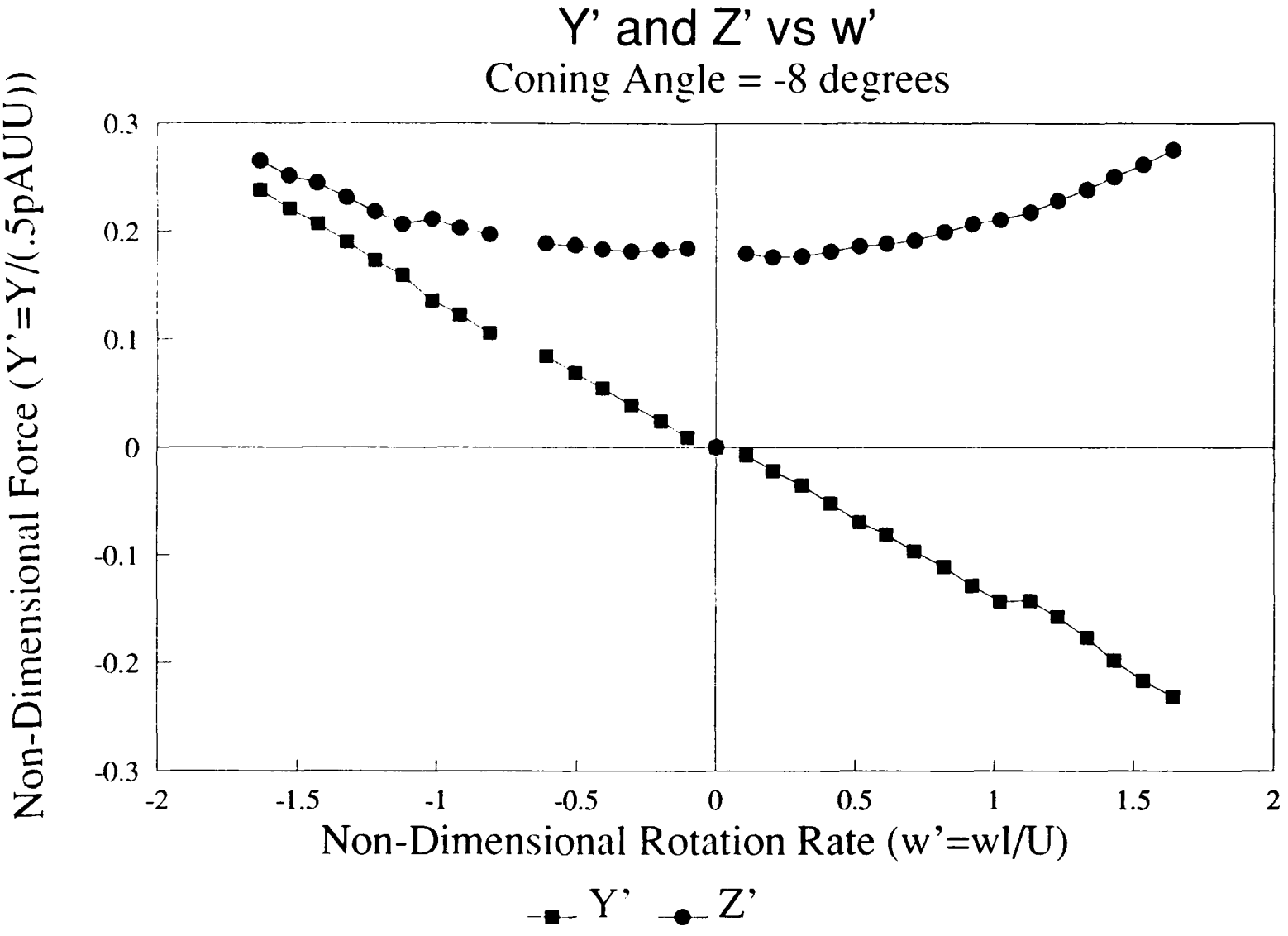

M' and N' vs w'
Coning Angle = -14 degrees
Non-Dimensional Moment (M'=M/(.5pAlUU))
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
M'
N'

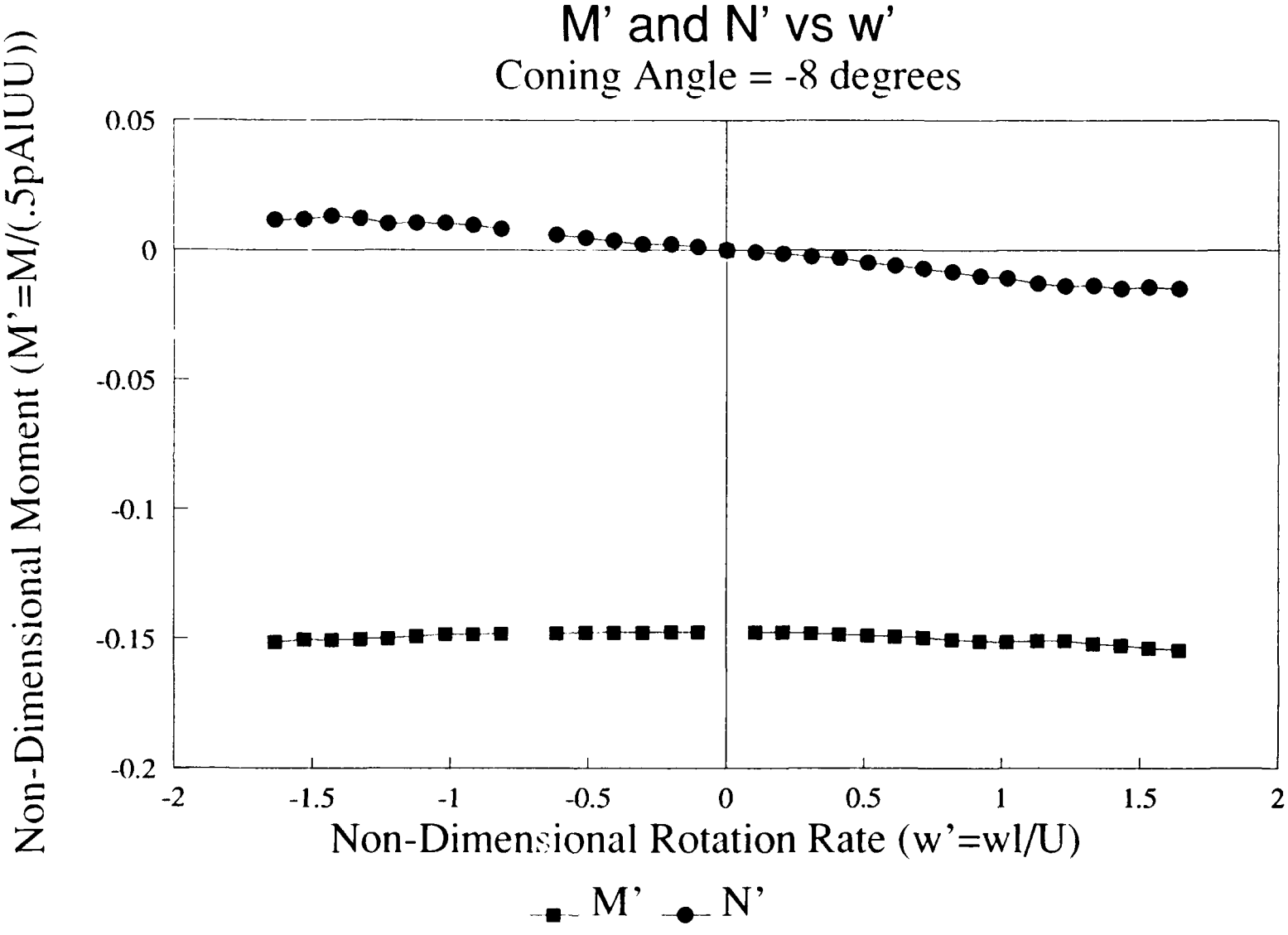

Y' and Z' vs w'
Coning Angle = -12 degrees
Non-Dimensional Force (Y'=Y/(.5pAUU))
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
Y'
Z'

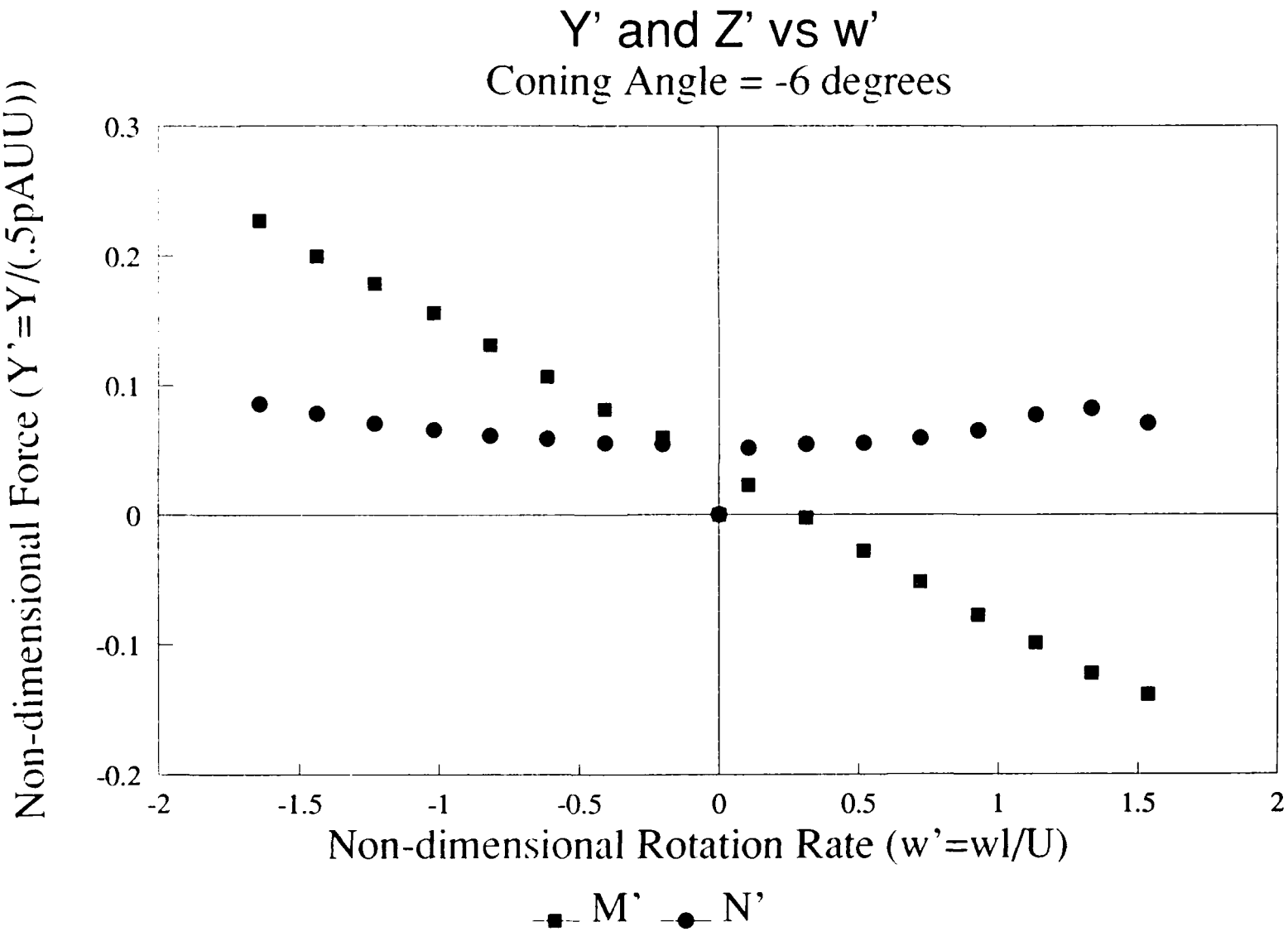

M' and N' vs w'
Coning Angle = -12 degrees
Non-Dimensional Moment (M'=M/(.5pAlUU))
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
M'
N'

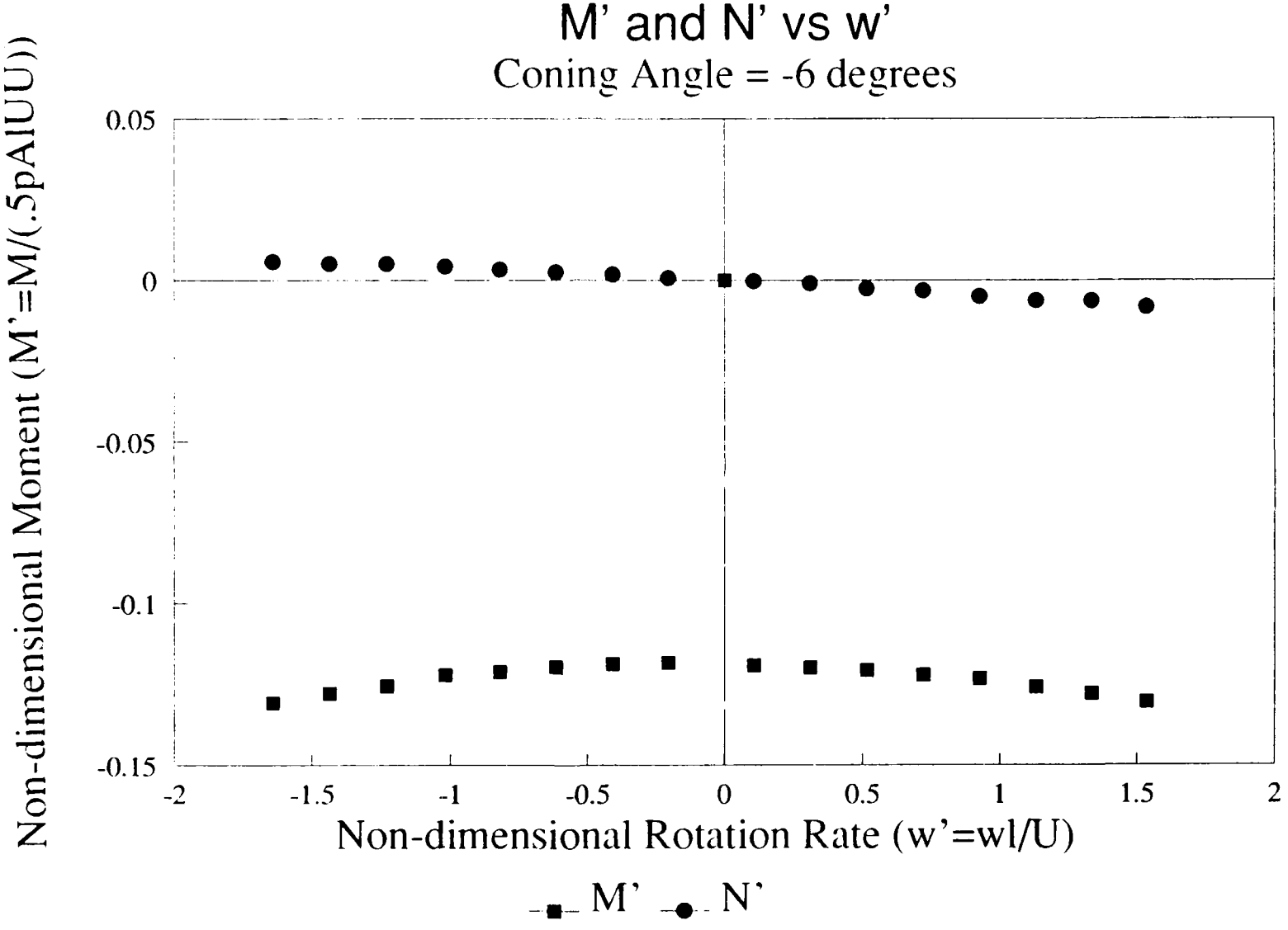

Y' and Z' vs w'
Coning Angle = -10 degrees
Non-Dimensional Force (Y'=Y/(.5pAUU))
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
Y'
Z'

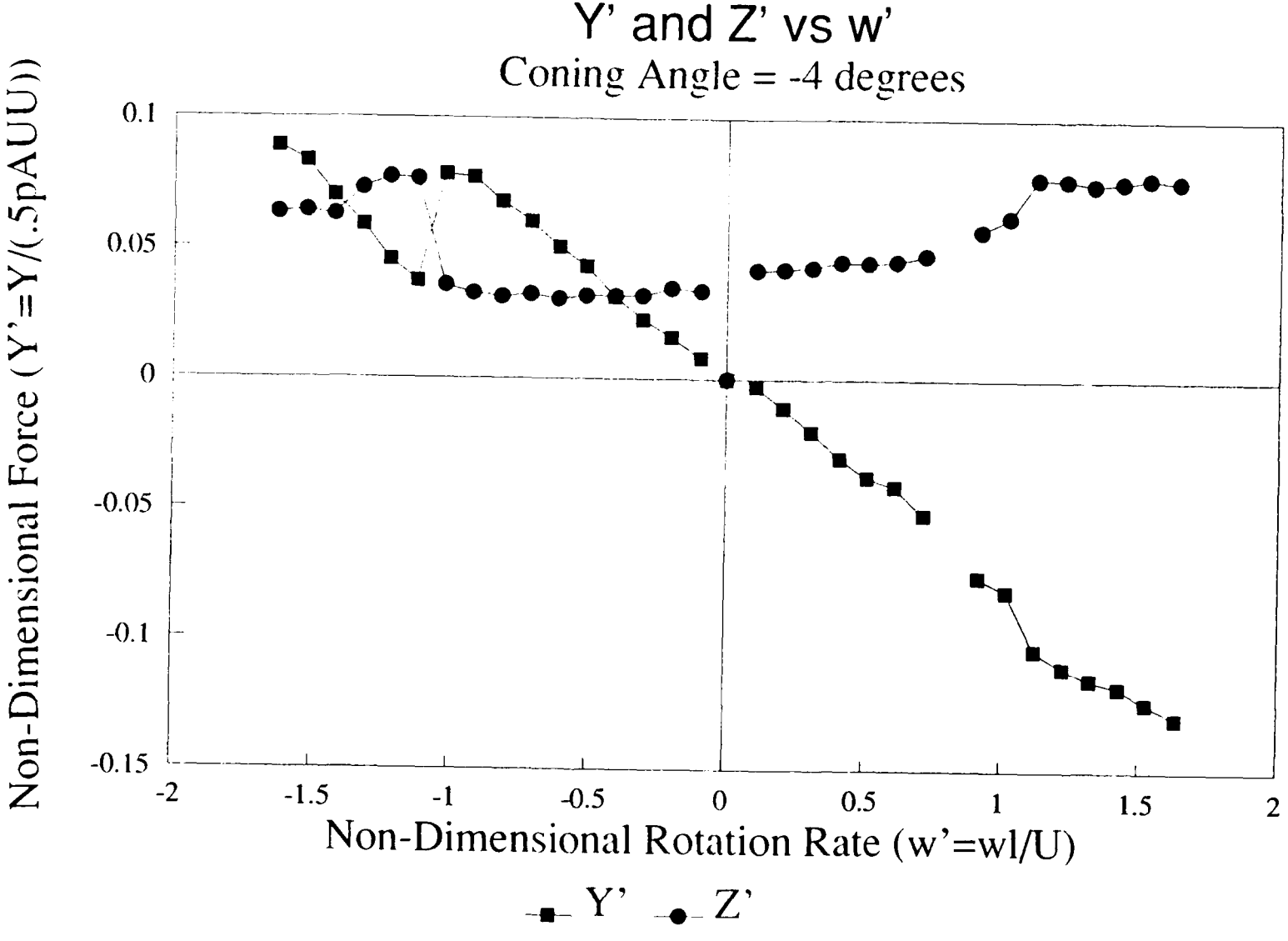

M' and N' vs w'
Coning Angle = -10 degrees
Non-Dimensional Moment (M'=M/(.5pAlUU))
0.05
0
-0.05
-0.1
-0.15
-0.2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
M'
N'

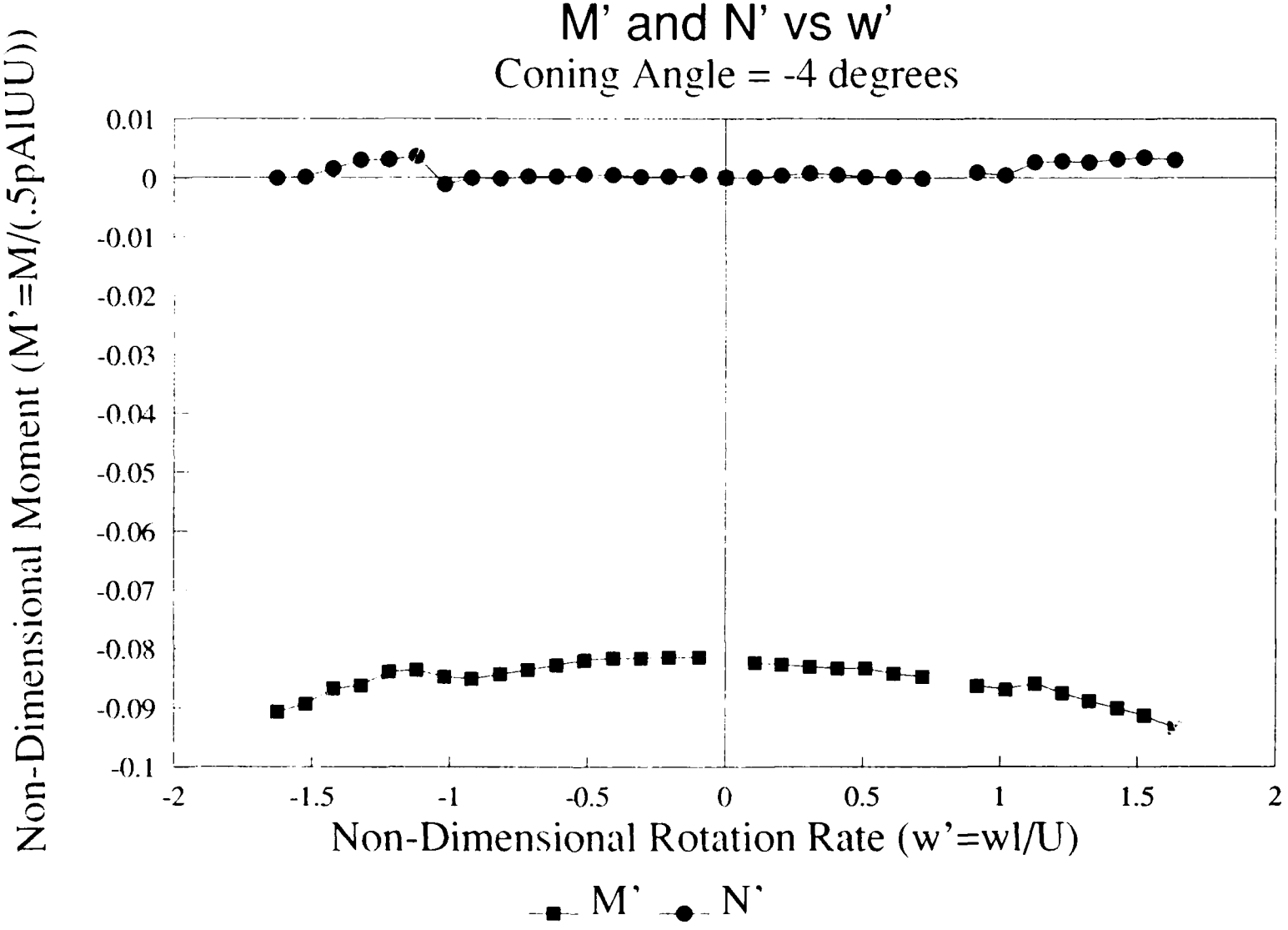

Y' and Z' vs w'
Coning Angle = -8 degrees
Non-Dimensional Force (Y'=Y/(.5pAUU))
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
Y'
Z'

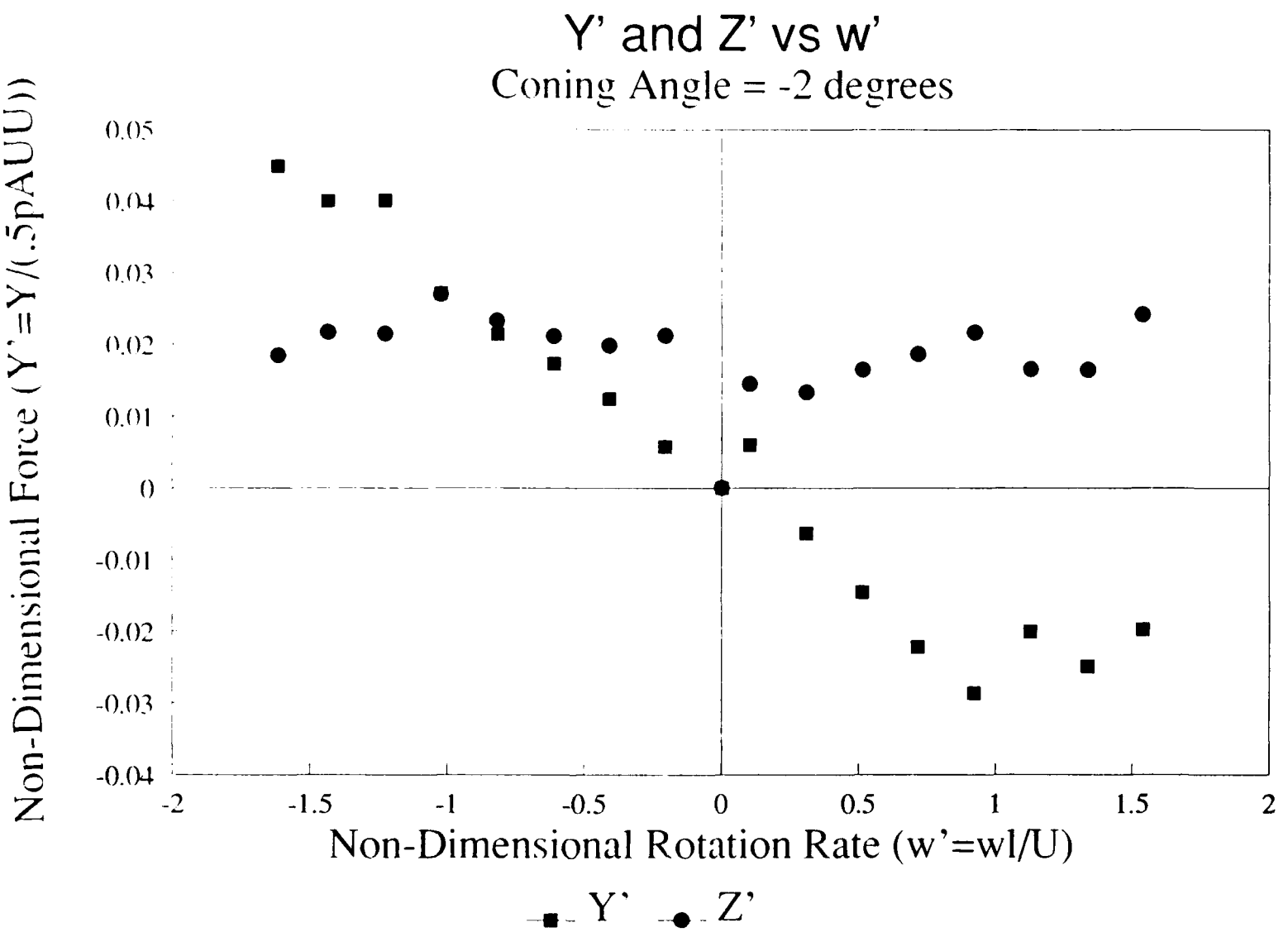

M' and N' vs w'
Coning Angle = -8 degrees
Non-Dimensional Moment (M'=M/(.5pAlUU))
0.05
0
-0.05
-0.1
-0.15
-0.2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
M'
N'

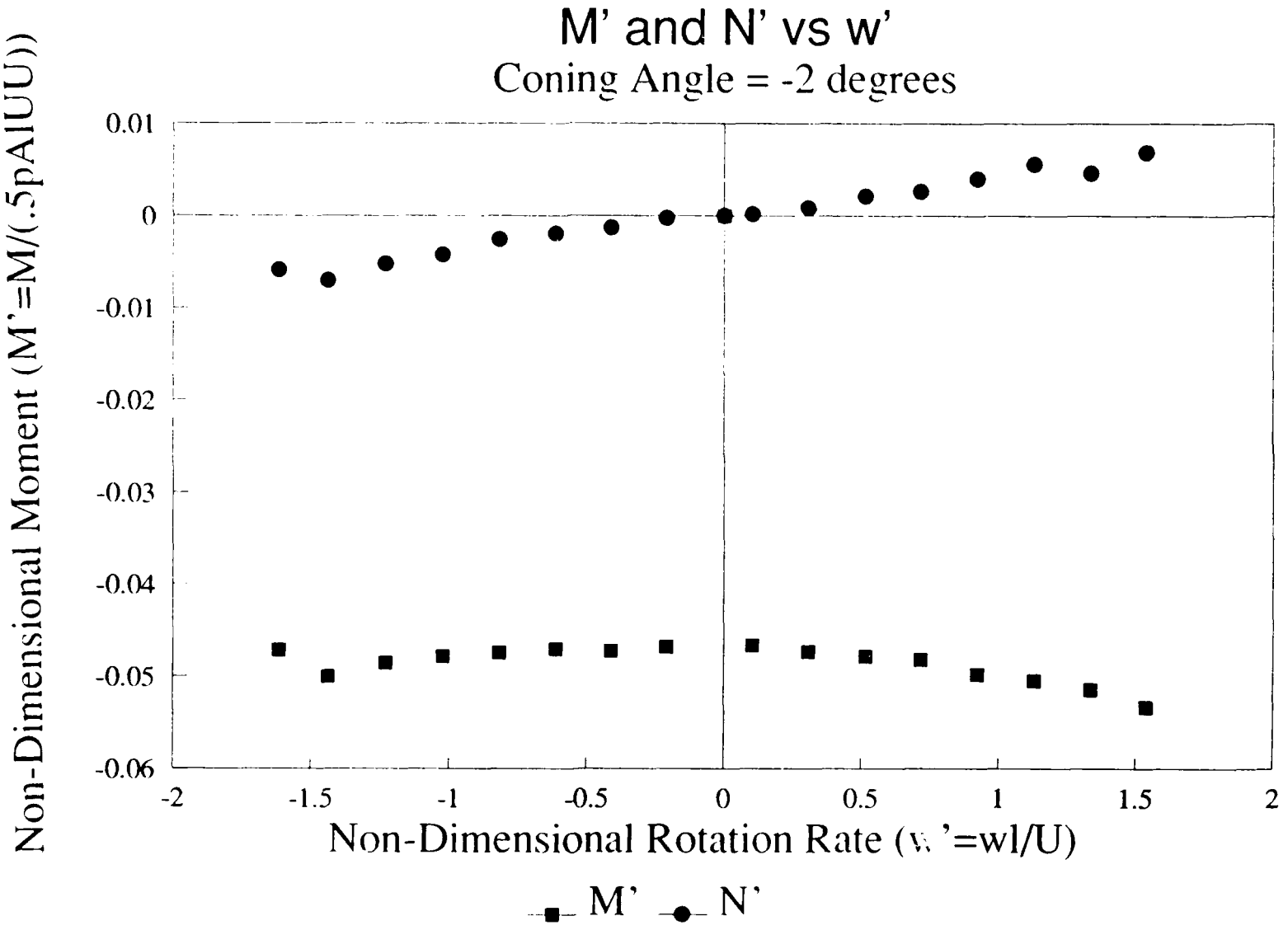

Y' and Z' vs w'
Coning Angle = -6 degrees
Non-dimensional Force (Y'=Y/(.5pAUU))
0.3
0.2
0.1
0
-0.1
-0.2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-dimensional Rotation Rate (w'=wl/U)
M'
N'

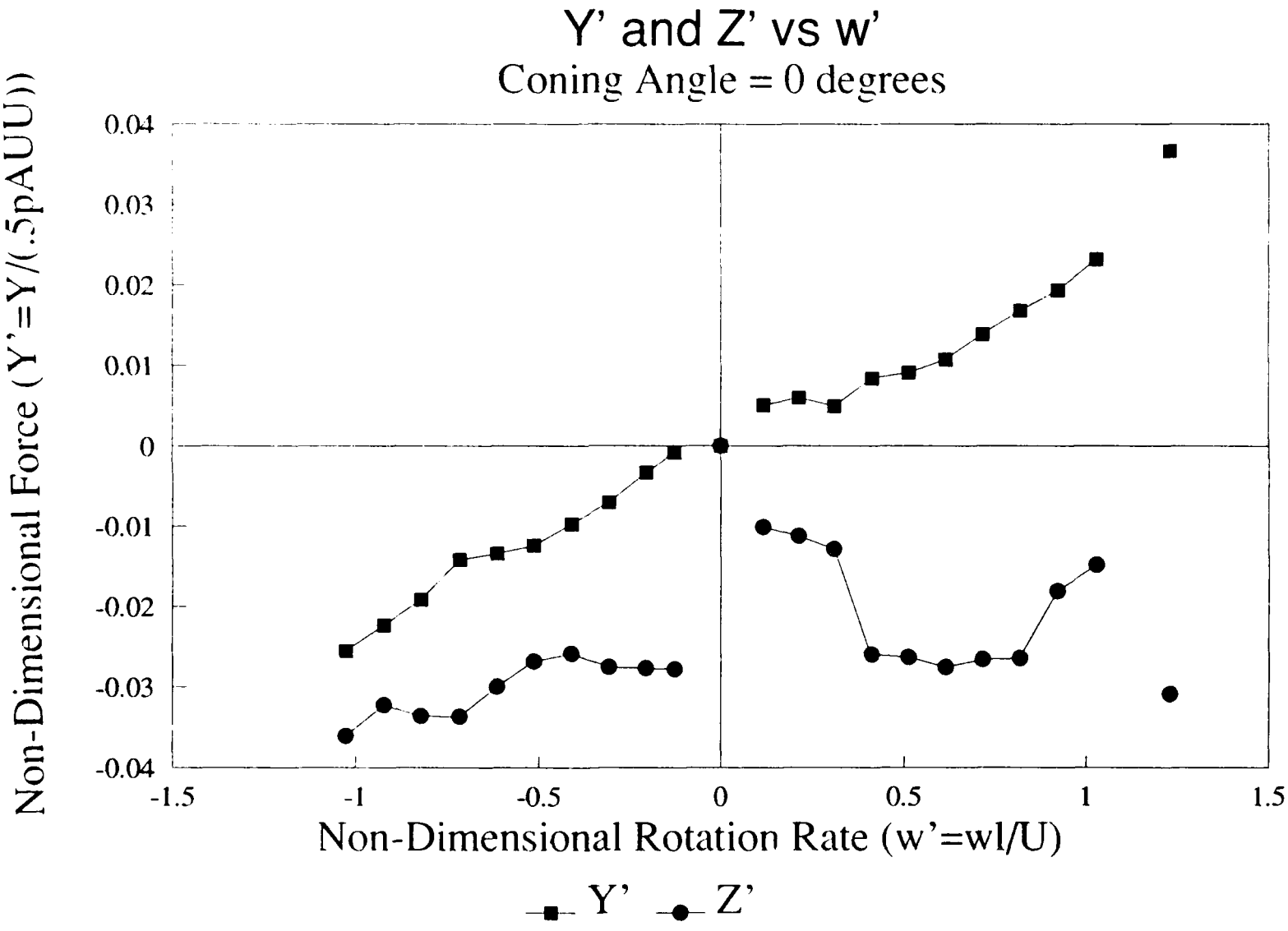

M' and N' vs w'
Coning Angle = -6 degrees
Non-dimensional Moment (M'=M/(.5pAlUU))
0.05
0
-0.05
-0.1
-0.15
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-dimensional Rotation Rate (w'=wl/U)
M'
N'

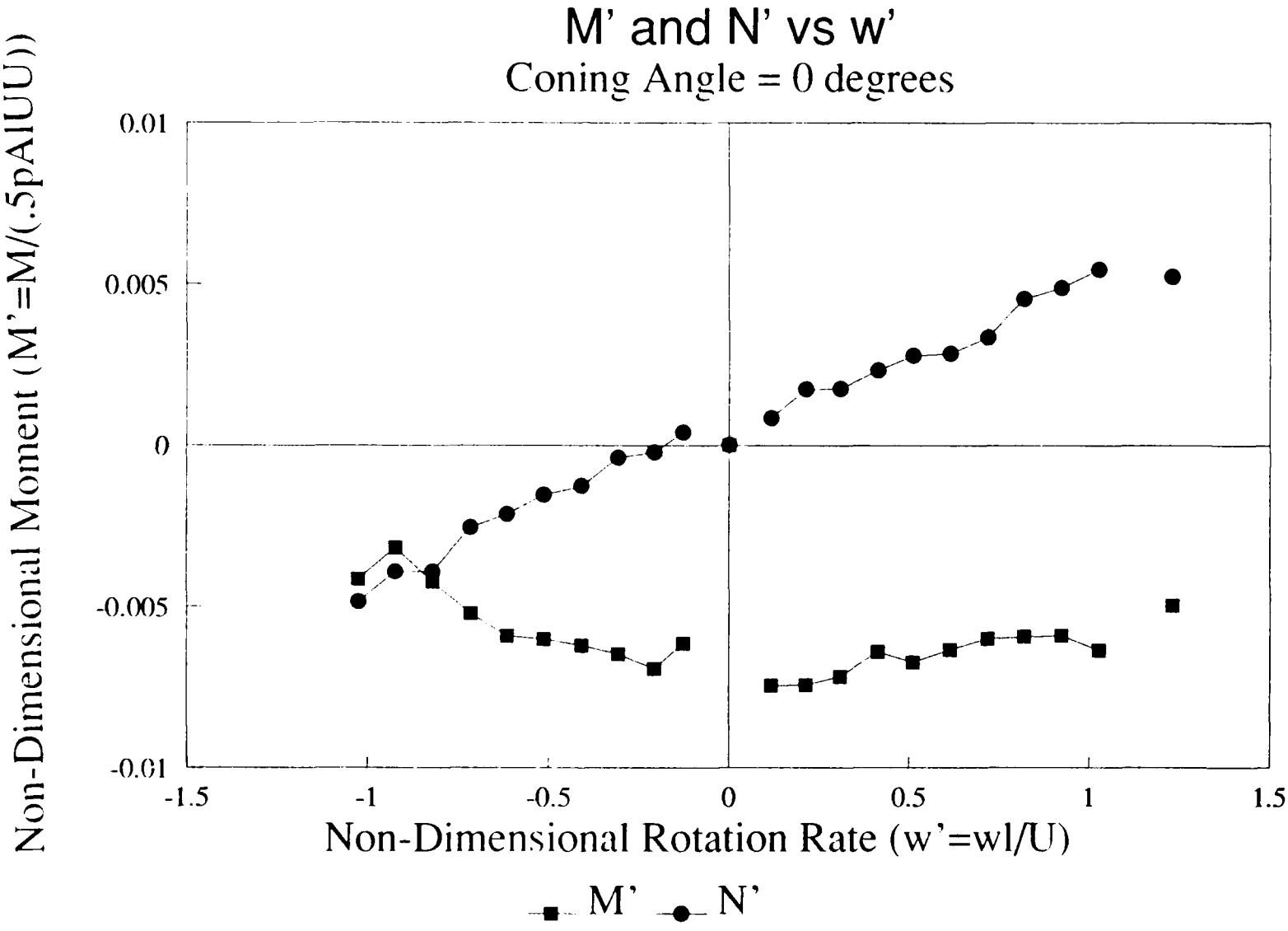

Y' and Z' vs w'
Coning Angle = -4 degrees
Non-Dimensional Force (Y'=Y/(.5pAUU))
0.1
0.05
0
-0.05
-0.1
-0.15
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
Y'
Z'

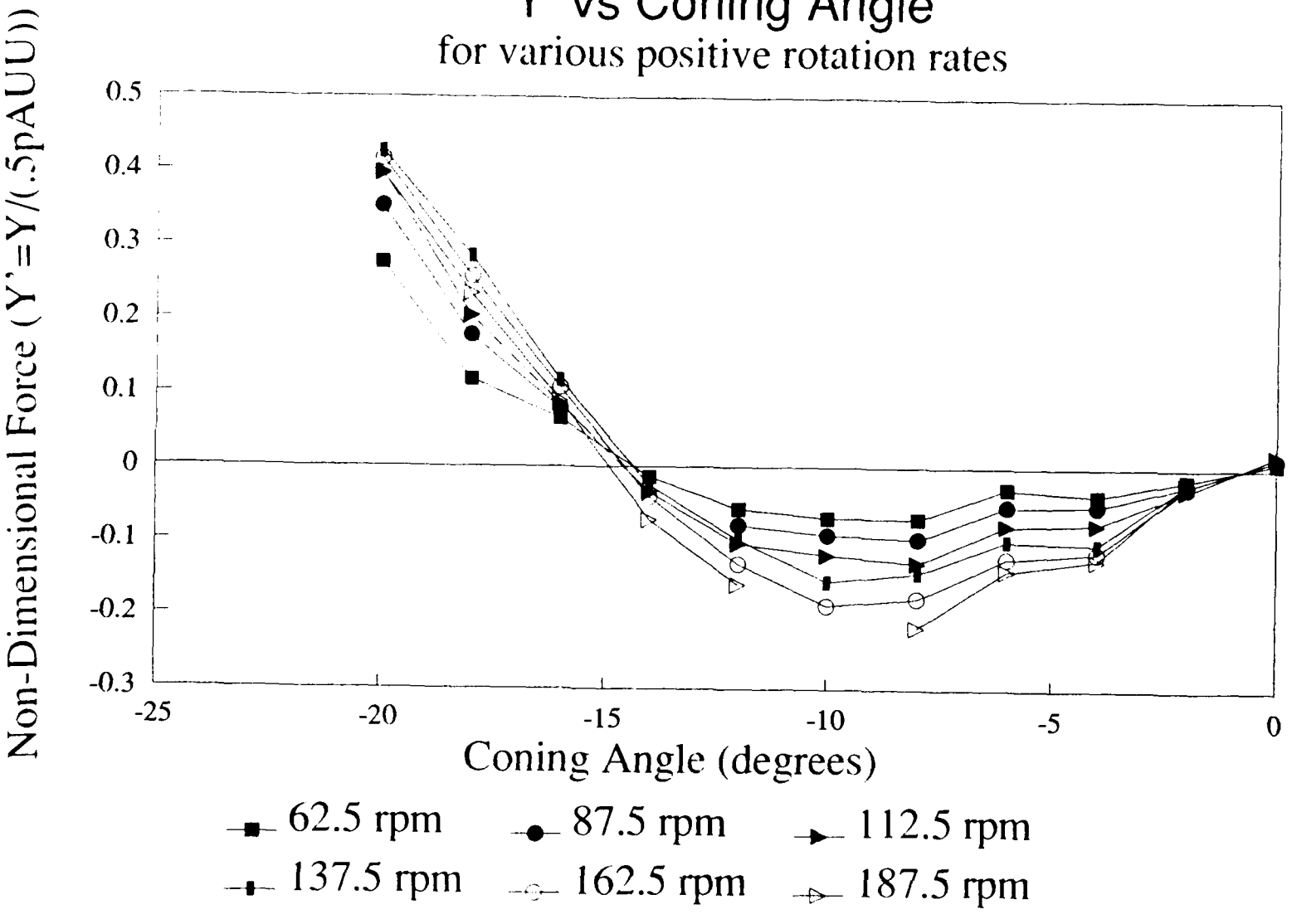

M' and N' vs w'
Coning Angle = -4 degrees
Non-Dimensional Moment (M'=M/(.5pAlUU))
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
-0.09
-0.1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
M'
N'

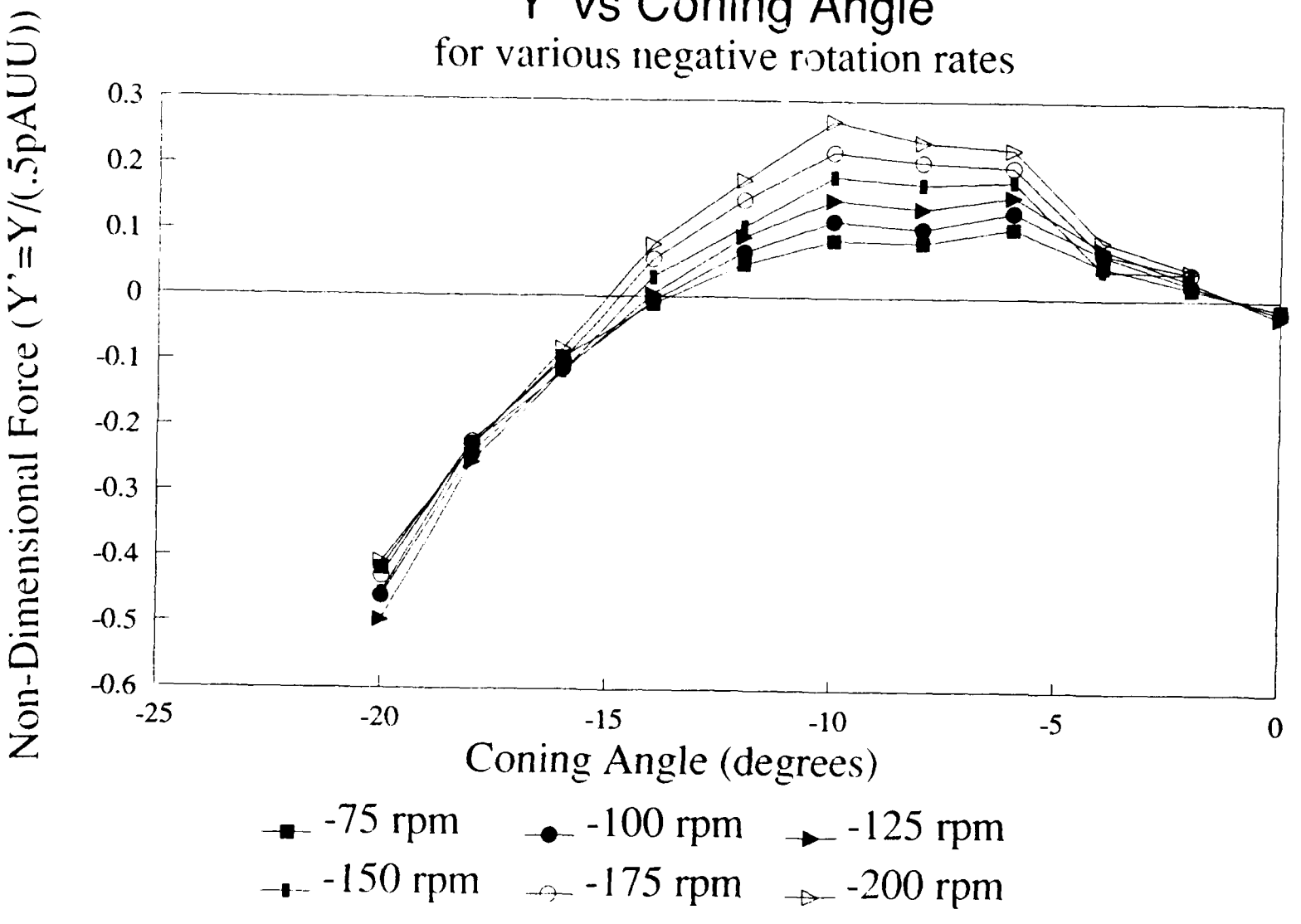

Y' and Z' vs w'
Coning Angle = -2 degrees
Non-Dimensional Force (Y'=Y/(.5pAUU))
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
Y'
Z'

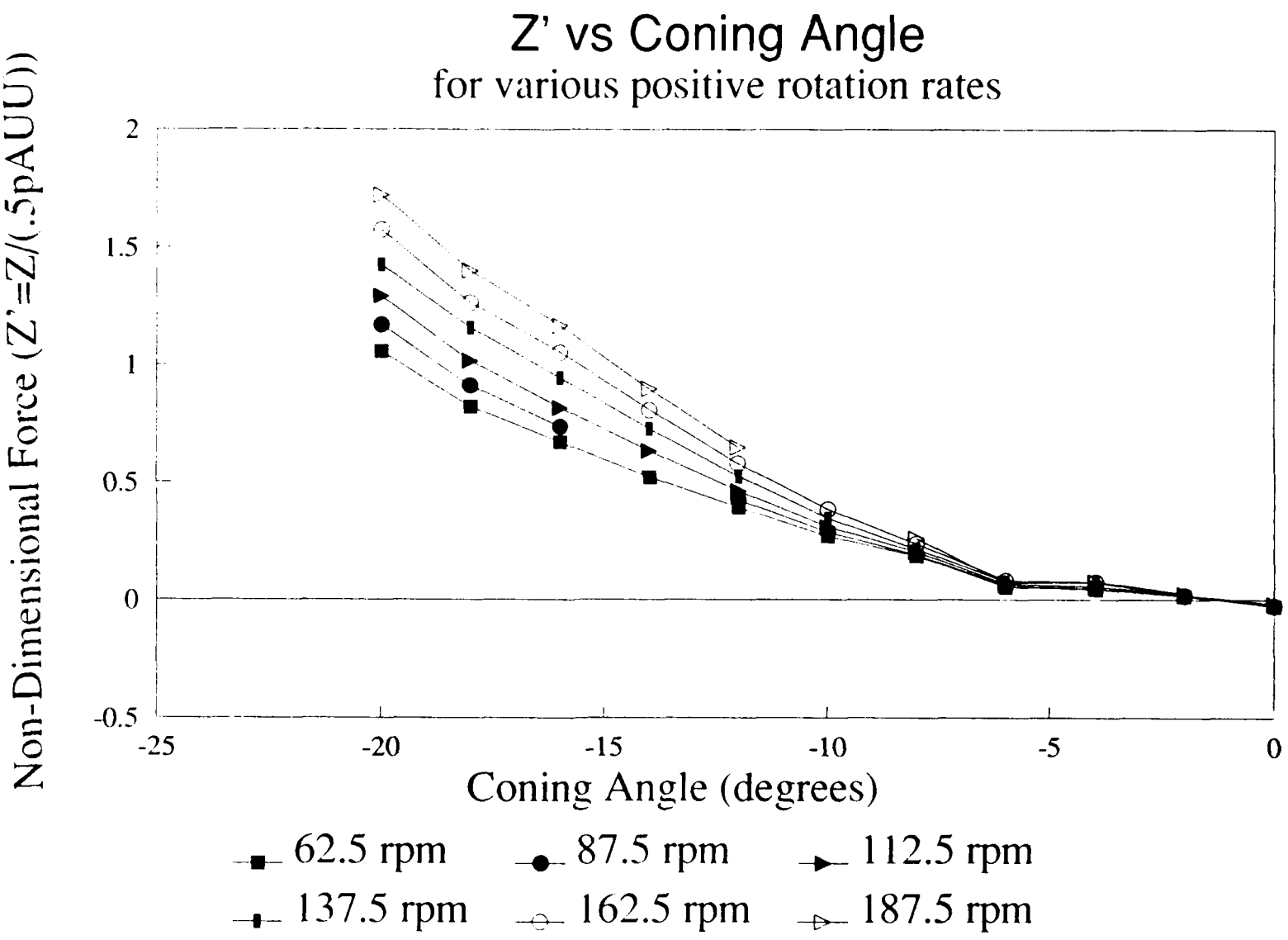

M' and N' vs w'
Coning Angle = -2 degrees
Non-Dimensional Moment (M'=M/(.5pAlUU))
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Non-Dimensional Rotation Rate (w'=wl/U)
M'
N'

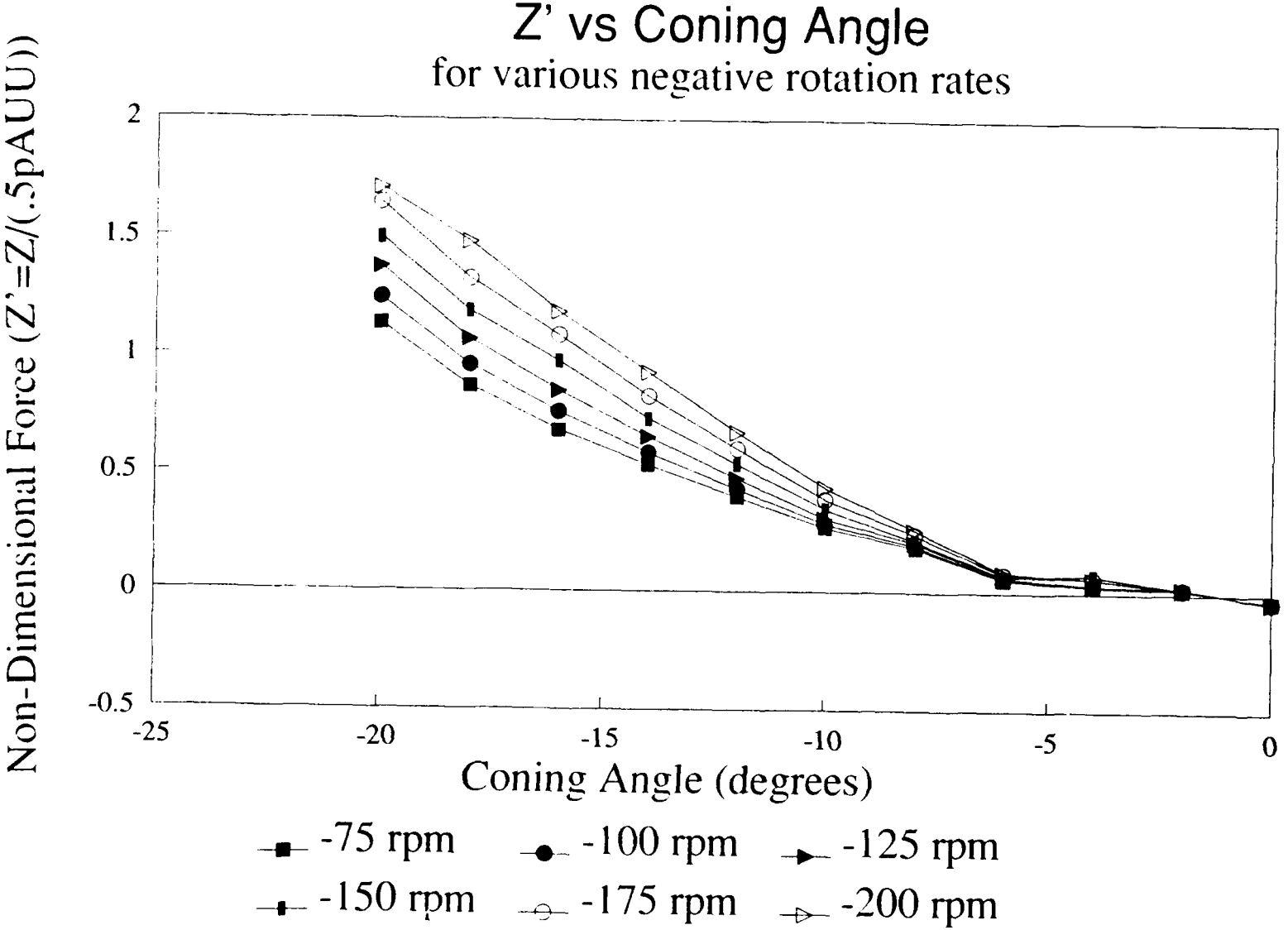

Y' and Z' vs w'
Coning Angle = 0 degrees
Non-Dimensional Force (Y'=Y/(.5pAUU))
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-1.5
-1
-0.5
0
0.5
1
1.5
Non-Dimensional Rotation Rate (w'=wl/U)
Y'
Z'

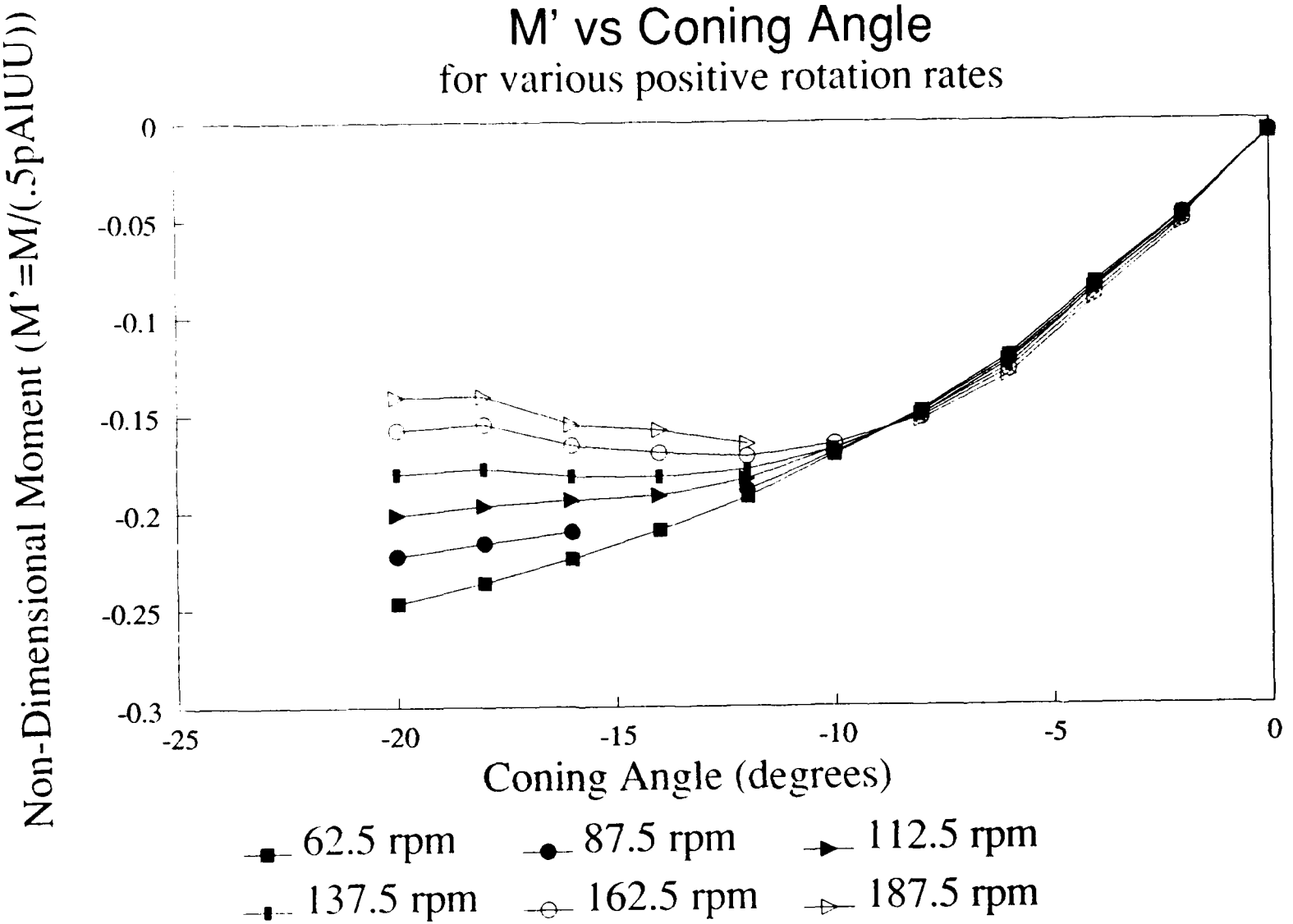

M' and N' vs w'
Coning Angle = 0 degrees
Non-Dimensional Moment (M'=M/(.5pAlUU))
0.01
0.005
0
-0.005
-0.01
-1.5
-1
-0.5
0
0.5
1
1.5
Non-Dimensional Rotation Rate (w'=wl/U)
M'
N'

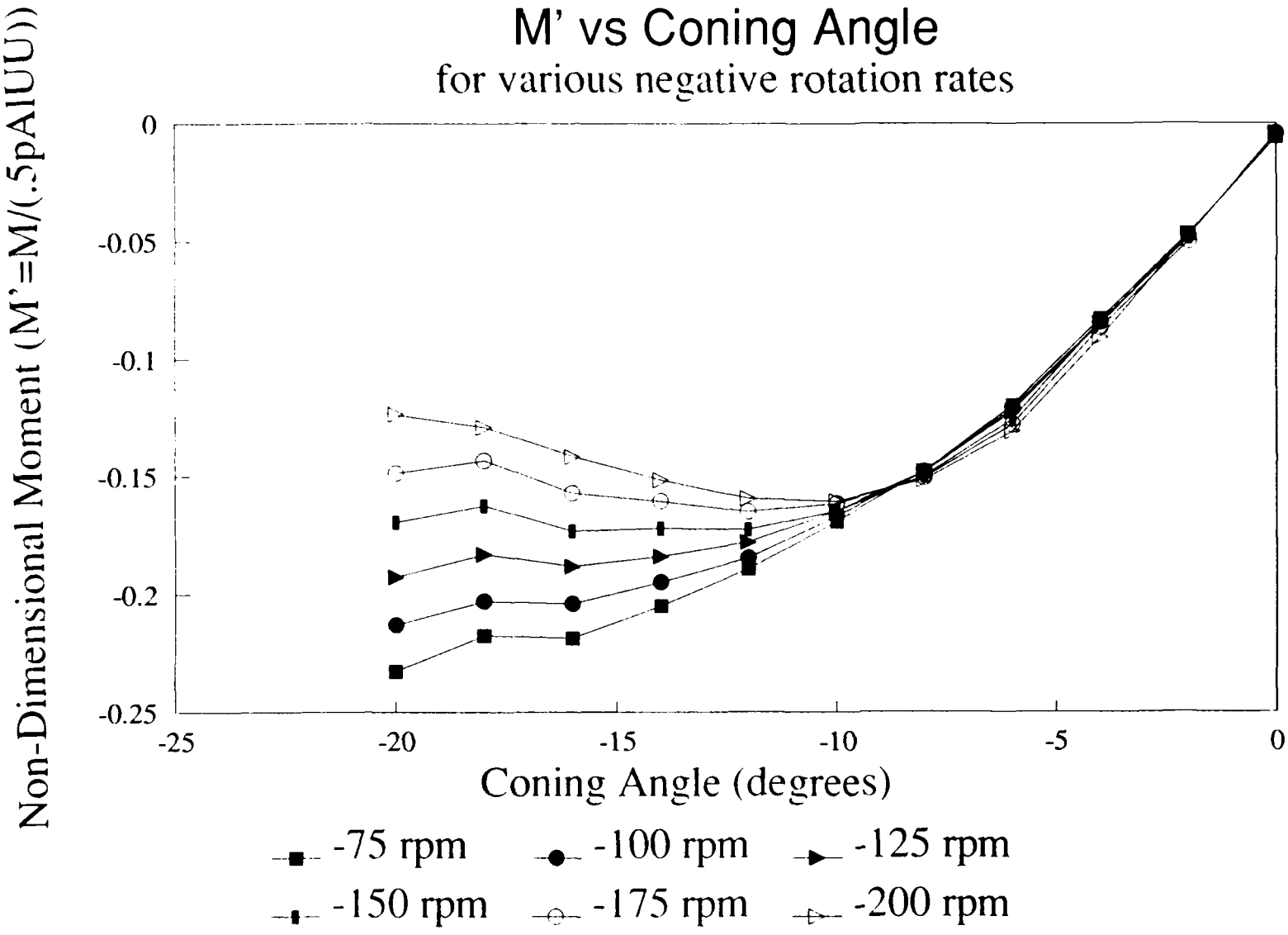

Y' vs Coning Angle
for various positive rotation rates
Non-Dimensional Force (Y'=Y/(.5pAUU))
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-25
-20
-15
-10
-5
0
Coning Angle (degrees)
62.5 rpm
87.5 rpm
112.5 rpm
137.5 rpm
162.5 rpm
187.5 rpm

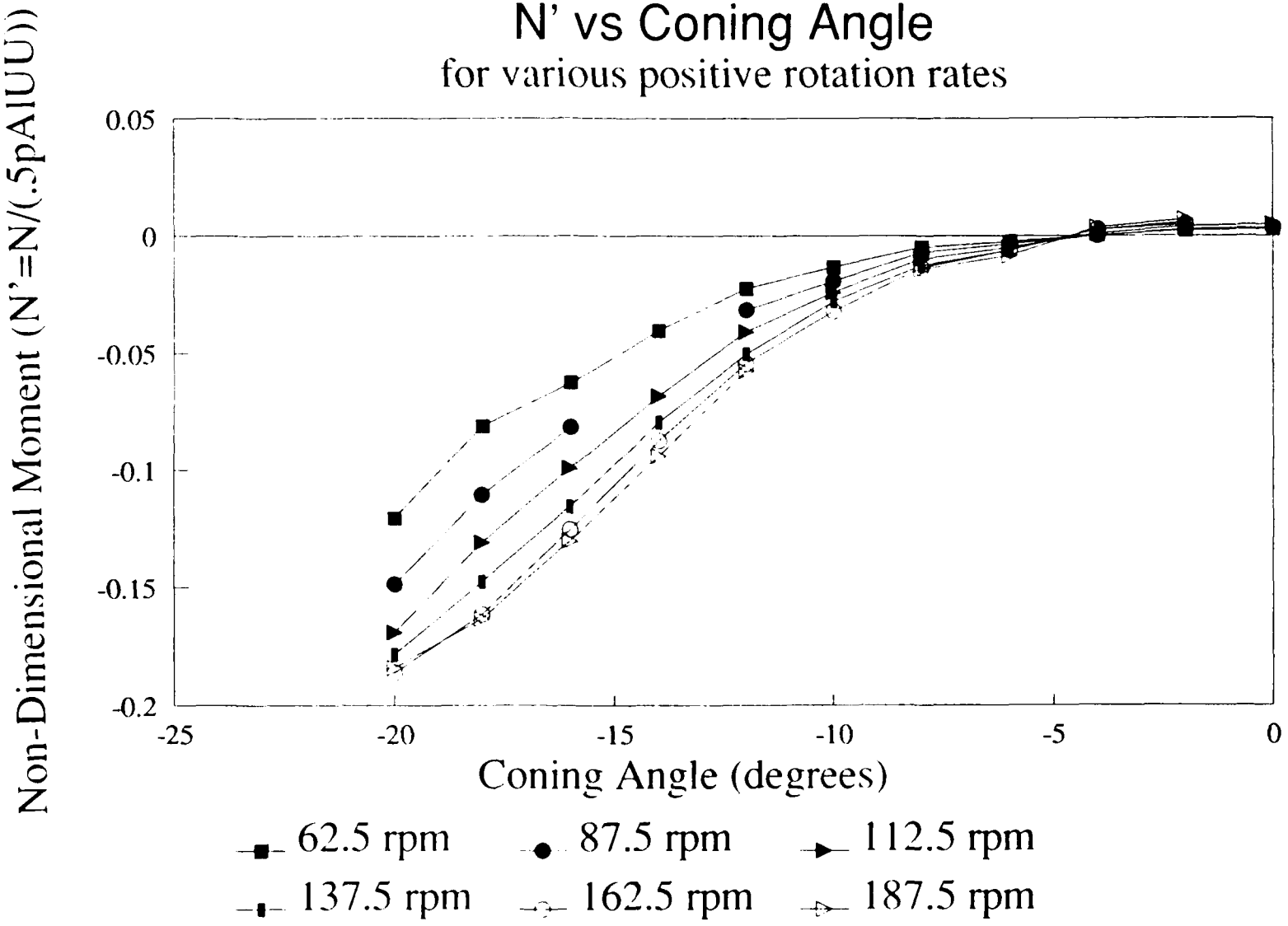

Y' vs Coning Angle
for various negative rotation rates
Non-Dimensional Force (Y'=Y/(.5pAUU))
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-25
-20
-15
-10
-5
0
Coning Angle (degrees)
-75 rpm
-100 rpm
-125 rpm
-150 rpm
-175 rpm
-200 rpm

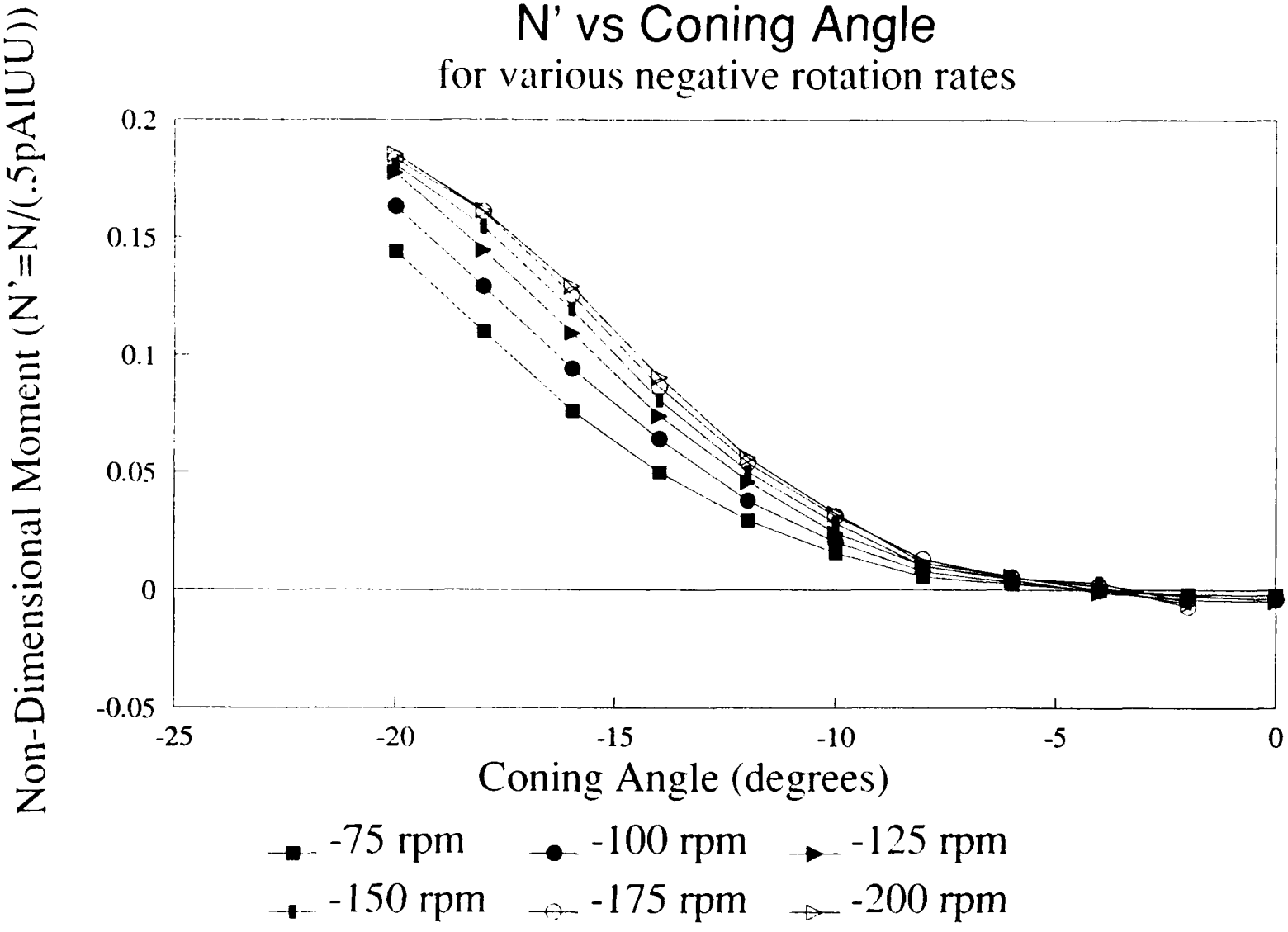

Z' vs Coning Angle
for various positive rotation rates
Non-Dimensional Force (Z'=Z/(.5pAUU))
2
1.5
1
0.5
0
-0.5
-25
-20
-15
-10
-5
0
Coning Angle (degrees)
62.5 rpm
87.5 rpm
112.5 rpm
137.5 rpm
162.5 rpm
187.5 rpm


Z' vs Coning Angle
for various negative rotation rates
Non-Dimensional Force (Z'=Z/(.5pAUU))
2
1.5
1
0.5
0
-0.5
-25
-20
-15
-10
-5
0
Coning Angle (degrees)
-75 rpm
-100 rpm
-125 rpm
-150 rpm
-175 rpm
-200 rpm


M' vs Coning Angle
for various positive rotation rates
Non-Dimensional Moment (M'=M/(.5pAlUU))
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-25
-20
-15
-10
-5
0
Coning Angle (degrees)
62.5 rpm
87.5 rpm
112.5 rpm
137.5 rpm
162.5 rpm
187.5 rpm


M' vs Coning Angle
for various negative rotation rates
Non-Dimensional Moment (M'=M/(.5pAlUU))
0
-0.05
-0.1
-0.15
-0.2
-0.25
-25
-20
-15
-10
-5
0
Coning Angle (degrees)
-75 rpm
-100 rpm
-125 rpm
-150 rpm
-175 rpm
-200 rpm


N' vs Coning Angle
for various positive rotation rates
Non-Dimensional Moment (N'=N/(.5pAlUU))
0.05
0
-0.05
-0.1
-0.15
-0.2
-25
-20
-15
-10
-5
0
Coning Angle (degrees)
62.5 rpm
87.5 rpm
112.5 rpm
137.5 rpm
162.5 rpm
187.5 rpm


N' vs Coning Angle
for various negative rotation rates
Non-Dimensional Moment (N'=N/(.5pAlUU))
0.2
0.15
0.1
0.05
0
-0.05
-25
-20
-15
-10
-5
0
Coning Angle (degrees)
-75 rpm
-100 rpm
-125 rpm
-150 rpm
-175 rpm
-200 rpm

Dimensional Load Data For Forward Rotation at Coning Angle = -20 degrees

Z	M	Y	N	K	X	Vel	rpm
29.8635	120.2937	5.6698	-14.1526	-70.5243	5.8486	25.00	0.00
21.6572	157.0398	-0.3844	9.9919	-0.0891	3.0625	24.84	12.49
22.0690	152.7623	-2.2657	27.5375	-0.1452	3.0097	24.76	24.44
23.2043	149.7088	-4.0424	43.5093	-0.1963	3.0368	24.92	37.15
24.1073	145.3647	-5.5313	56.9470	1.0662	2.9198	24.99	49.59
25.3857	139.1943	-6.6393	67.8386	1.3369	2.8569	25.03	62.48
26.4662	131.5774	-7.5409	75.8866	1.3645	2.8347	24.94	74.86
27.9149	124.9832	-8.4043	83.4510	1.2366	2.7572	24.97	87.29
29.4548	119.0514	-9.0472	89.8170	1.1090	2.7524	24.99	99.79
30.9940	113.6491	-9.5422	95.1555	0.8849	2.6615	25.02	112.29
32.6480	108.1509	-9.9119	99.9258	1.0912	2.5273	25.04	124.76
33.0693	98.1752	-9.8617	97.1098	1.3564	1.9363	24.59	137.61
36.5185	86.0031	-9.6476	101.4157	1.6899	1.9256	24.60	162.62
39.7711	76.4031	-9.1482	99.8649	1.8745	1.8825	24.55	187.35

Dimensional Load Data For Reverse Rotation at Coning Angle = -20 degrees

Z	M	Y	N	K	X	Vel	rpm
21.7201	156.2354	3.6958	-25.8319	1.0880	2.9303	24.80	12.07
22.1691	150.9327	5.4474	-41.4976	1.0386	2.8453	24.71	25.29
22.8038	143.5899	6.7499	-53.8923	1.0800	2.7385	24.57	37.47
24.4541	142.0811	8.2356	-64.4831	1.1346	2.7479	24.86	49.81
25.3329	133.9430	8.9463	-72.2050	1.0754	2.6924	24.71	62.31
26.4713	127.8221	9.7383	-79.0438	0.9890	2.5827	24.69	74.81
28.3068	125.1182	10.4564	-86.2570	1.0077	2.5668	24.94	87.29
29.7342	119.5065	10.9772	-91.5532	1.0904	2.5465	24.96	99.84
31.1433	113.6268	11.4509	-95.5391	1.1916	2.4435	24.96	112.32
32.8140	108.2342	11.8524	-99.6394	1.1542	2.4019	24.97	124.64
35.1353	93.2843	10.6662	-99.6543	0.2363	2.2336	24.73	150.34
38.1947	81.0946	9.9558	-100.0908	1.6024	2.3078	24.62	175.28
39.7279	67.4447	9.4619	-101.2196	2.0170	2.3769	24.63	186.96

Non-Dimensional Load Data For Forward Rotation at Coning Angle = -20 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
1.2468	-0.2137	-0.2367	0.0251	0.1253	0.2442	25.00	0.0000
0.9159	-0.2826	0.0163	-0.0180	0.0002	0.1295	24.84	0.1031
0.9394	-0.2767	0.0964	-0.0499	0.0003	0.1281	24.76	0.2024
0.9750	-0.2677	0.1699	-0.0778	0.0004	0.1276	24.92	0.3057
1.0073	-0.2585	0.2311	-0.1013	-0.0019	0.1220	24.99	0.4070
1.0573	-0.2467	0.2765	-0.1202	-0.0024	0.1190	25.03	0.5119
1.1103	-0.2349	0.3164	-0.1355	-0.0024	0.1189	24.94	0.6156
1.1683	-0.2226	0.3517	-0.1486	-0.0022	0.1154	24.97	0.7169
1.2308	-0.2117	0.3780	-0.1597	-0.0020	0.1150	24.99	0.8189
1.2920	-0.2016	0.3978	-0.1688	-0.0016	0.1109	25.02	0.9204
1.3587	-0.1915	0.4125	-0.1770	-0.0019	0.1052	25.04	1.0218
1.4271	-0.1803	0.4256	-0.1783	-0.0025	0.0836	24.59	1.1476
1.5747	-0.1578	0.4160	-0.1861	-0.0031	0.0830	24.60	1.3557
1.7219	-0.1408	0.3961	-0.1840	-0.0035	0.0815	24.55	1.5650

Non-Dimensional Load Data For Reverse Rotation at Coning Angle = -20 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.9215	-0.2821	-0.1568	0.0466	-0.0020	0.1247	24.80	-0.0998
0.9474	-0.2745	-0.2328	0.0755	-0.0019	0.1216	24.71	-0.2099
0.9857	-0.2641	-0.2918	0.0991	-0.0020	0.1184	24.57	-0.3127
1.0325	-0.2553	-0.3477	0.1159	-0.0020	0.1160	24.86	-0.4109
1.0827	-0.2436	-0.3823	0.1313	-0.0020	0.1151	24.71	-0.5171
1.1331	-0.2328	-0.4169	0.1440	-0.0018	0.1106	24.69	-0.6214
1.1875	-0.2234	-0.4387	0.1540	-0.0018	0.1077	24.94	-0.7178
1.2454	-0.2130	-0.4598	0.1632	-0.0018	0.1067	24.96	-0.8203
1.3044	-0.2025	-0.4796	0.1713	-0.0021	0.1023	24.96	-0.9228
1.3733	-0.1928	-0.4960	0.1774	-0.0021	0.1005	24.97	-1.0237
1.4991	-0.1694	-0.4551	0.1809	-0.0004	0.0953	24.73	-1.2467
1.6443	-0.1486	-0.4286	0.1834	-0.0029	0.0994	24.62	-1.4600
1.7089	-0.1235	-0.4070	0.1853	-0.0037	0.1022	24.63	-1.5507

Dimensional Load Data For Forward Rotation at Coning Angle = -18 degrees

Z	M	Y	N	K	X	Vel	rpm
25.9381	111.1323	5.9220	-13.1686	-68.6348	5.5629	25.00	0.00
17.2494	145.5075	0.5765	2.5230	-0.2561	2.7289	24.96	11.97
17.6199	144.9466	-0.3285	13.9721	-0.2575	2.7523	25.03	24.92
18.2902	142.6019	-1.3722	26.0677	-0.2456	2.7443	25.08	37.45
18.9646	139.0293	-2.1861	36.6745	-0.3302	2.7032	25.11	49.71
19.9192	134.7609	-2.8727	46.2410	-0.3192	2.7369	25.16	62.32
21.0715	128.9478	-3.9260	55.9037	-0.2051	2.6572	25.19	74.80
22.1366	123.2874	-4.3114	62.9779	-0.3028	2.6247	25.17	87.18
23.4583	118.4867	-4.6821	69.2534	-0.3549	2.6022	25.23	99.58
24.8624	112.9850	-4.9934	75.0128	-0.3641	2.5681	25.25	112.27
26.2152	107.0345	-5.0505	79.7020	-0.4550	2.5292	25.25	124.81
27.6305	99.7304	-6.8119	82.7423	-0.0918	2.2260	24.95	137.61
29.7603	85.6253	-6.0511	89.1423	-0.7084	1.8767	24.78	162.27
32.8455	77.4997	-5.4916	90.0893	0.2058	1.7908	24.75	187.40

Dimensional Load Data For Reverse Rotation at Coning Angle = -18 degrees

Z	M	Y	N	K	X	Vel	rpm
17.2962	143.9532	2.1004	-17.8305	-0.5734	2.6973	24.91	12.57
17.7047	141.4426	2.9855	-29.5615	-0.4945	2.7067	24.93	25.31
18.1011	137.0582	3.7136	-38.8640	-0.4833	2.6213	24.87	37.56
18.8370	132.9159	4.4362	-47.5928	-0.4580	2.5778	24.86	50.08
19.9097	130.3653	5.0653	-55.3043	-0.5653	2.5446	25.02	62.60
20.8026	122.5079	5.3855	-61.9187	-0.5085	2.4925	25.00	75.02
21.8676	119.9527	5.4870	-67.4755	-0.6651	2.4433	25.03	87.29
23.0739	114.7627	5.8167	-72.9133	-0.6907	2.3722	25.05	99.92
24.4167	108.9049	6.0218	-77.7025	-0.7735	2.3296	25.05	112.49
25.6713	103.4438	6.1319	-81.7204	-0.6376	2.2857	25.05	124.96
27.6663	88.9314	5.2816	-84.5274	-0.4631	1.7302	24.65	150.00
30.8951	78.5507	5.2125	-88.2178	-0.0662	1.6276	24.67	174.69
34.3666	70.3742	5.3820	-88.1258	0.8533	1.3870	24.61	199.86

Non-Dimensional Load Data For Forward Rotation at Coning Angle = -18 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
1.0829	-0.1974	-0.2473	0.0234	0.1219	0.2323	25.00	0.0000
0.7225	-0.2593	-0.0241	-0.0045	0.0005	0.1143	24.96	0.0983
0.7339	-0.2569	0.0137	-0.0248	0.0005	0.1146	25.03	0.2042
0.7588	-0.2517	0.0569	-0.0460	0.0004	0.1138	25.08	0.3062
0.7849	-0.2448	0.0905	-0.0646	0.0006	0.1119	25.11	0.4060
0.8211	-0.2364	0.1184	-0.0811	0.0006	0.1128	25.16	0.5080
0.8665	-0.2257	0.1615	-0.0978	0.0004	0.1093	25.19	0.6090
0.9118	-0.2161	0.1776	-0.1104	0.0005	0.1081	25.17	0.7103
0.9616	-0.2067	0.1919	-0.1208	0.0006	0.1067	25.23	0.8094
1.0176	-0.1968	0.2044	-0.1306	0.0006	0.1051	25.25	0.9118
1.0729	-0.1864	0.2067	-0.1388	0.0008	0.1035	25.25	1.0137
1.1582	-0.1779	0.2855	-0.1476	0.0002	0.0933	24.95	1.1311
1.2647	-0.1548	0.2571	-0.1612	0.0013	0.0798	24.78	1.3429
1.3992	-0.1405	0.2339	-0.1633	-0.0004	0.0763	24.75	1.5528

Non-Dimensional Load Data For Reverse Rotation at Coning Angle = -18 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.7274	-0.2576	-0.0883	0.0319	0.0010	0.1134	24.91	-0.1035
0.7433	-0.2527	-0.1253	0.0528	0.0009	0.1136	24.93	-0.2082
0.7637	-0.2461	-0.1567	0.0698	0.0009	0.1106	24.87	-0.3097
0.7954	-0.2388	-0.1873	0.0855	0.0008	0.1088	24.86	-0.4131
0.8299	-0.2312	-0.2111	0.0981	0.0010	0.1061	25.02	-0.5131
0.8685	-0.2177	-0.2249	0.1100	0.0009	0.1041	25.00	-0.6154
0.9108	-0.2126	-0.2285	0.1196	0.0012	0.1018	25.03	-0.7152
0.9595	-0.2031	-0.2419	0.1290	0.0012	0.0986	25.05	-0.8180
1.0154	-0.1927	-0.2504	0.1375	0.0014	0.0969	25.05	-0.9209
1.0675	-0.1831	-0.2550	0.1446	0.0011	0.0951	25.05	-1.0230
1.1881	-0.1625	-0.2268	0.1545	0.0008	0.0743	24.65	-1.2479
1.3246	-0.1433	-0.2235	0.1610	0.0001	0.0698	24.67	-1.4522
1.4807	-0.1290	-0.2319	0.1616	-0.0016	0.0598	24.61	-1.6654

Dimensional Load Data For Forward Rotation at Coning Angle = -16 degrees

Z	M	Y	N	K	X	Vel	rpm
22.0371	102.5002	5.3784	-12.0420	-66.7116	5.2042	25.00	0.00
14.4323	134.8958	-0.3332	7.2593	0.1373	2.4082	24.98	12.89
14.5958	133.6563	-0.6400	14.0342	0.0199	2.4309	25.02	25.03
15.0217	132.0031	-1.0639	21.7987	0.0602	2.4054	25.03	37.60
15.5543	129.3311	-1.3163	28.6361	-0.0054	2.4060	25.01	50.10
16.1014	126.0645	-1.5725	35.3193	0.1858	2.3888	25.00	62.65
16.8519	122.5147	-1.7617	41.1085	0.1258	2.3805	25.03	75.11
17.7150	118.9043	-1.9133	46.2813	0.1500	2.4126	25.06	87.35
18.5173	114.5240	-2.0546	51.7344	0.1690	2.2978	25.01	100.37
19.6734	109.5262	-2.0503	55.9119	0.1967	2.3506	25.04	112.75
20.8091	105.9355	-2.2496	60.7357	0.0673	2.2617	25.02	125.17
22.6463	102.3270	-2.8052	64.8749	-0.0170	2.5021	25.00	137.51
23.8631	97.9672	-2.7491	67.8010	-0.0922	2.4394	25.01	149.86
25.2426	93.3248	-2.5652	70.4197	-0.2205	2.4685	25.00	162.33
26.5978	89.0300	-2.2512	71.7536	-0.2127	2.4797	24.96	174.92
27.9903	87.2313	-2.1531	73.1711	-0.0318	2.3633	25.01	187.13

Dimensional Load Data For Reverse Rotation at Coning Angle = -16 degrees

Z	M	Y	N	K	X	Vel	rpm
14.2766	135.6110	0.7410	-9.4934	0.0785	2.4109	25.08	13.43
14.4084	134.6232	0.9706	-15.5882	-0.0109	2.4053	25.09	24.94
14.7464	132.8594	1.3840	-23.1634	0.0082	2.3887	25.11	37.46
15.2687	130.1648	1.6645	-30.5682	0.0353	2.3960	25.13	50.00
15.8087	125.5374	1.9190	-36.6911	-0.2009	2.2974	24.99	62.38
16.3250	122.7568	2.2309	-42.7389	-0.0731	2.2905	24.97	74.99
17.2441	118.9313	2.3798	-47.7262	-0.1663	2.2352	24.98	87.17
18.2243	114.8026	2.6557	-52.8973	0.0172	2.2048	24.99	99.85
19.2945	110.3171	2.6946	-57.5758	-0.1100	2.2083	24.99	112.54
20.3881	105.9378	2.7533	-61.4911	-0.1015	2.1196	25.00	124.94
23.4454	97.7201	2.7692	-67.3477	-0.5438	2.3961	25.03	149.91
24.7151	93.3619	2.4782	-69.4791	-0.5407	2.4751	25.06	162.58
26.1596	88.9024	2.3672	-71.0140	-0.5268	2.4353	25.07	174.83
27.5786	84.2574	2.1504	-71.9738	-0.3984	2.4668	25.01	187.34
28.4021	79.7329	1.9296	-72.8522	-0.5104	2.3314	25.01	195.25

Non-Dimensional Load Data For Forward Rotation at Coning Angle = -16 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.9201	-0.1821	-0.2246	0.0214	0.1185	0.2173	25.00	0.0000
0.6035	-0.2400	0.0139	-0.0129	-0.0002	0.1007	24.98	0.1058
0.6084	-0.2371	0.0267	-0.0249	0.0000	0.1013	25.02	0.2052
0.6257	-0.2340	0.0443	-0.0386	-0.0001	0.1002	25.03	0.3081
0.6489	-0.2296	0.0549	-0.0508	0.0000	0.1004	25.01	0.4108
0.6723	-0.2240	0.0657	-0.0627	-0.0003	0.0997	25.00	0.5139
0.7019	-0.2171	0.0734	-0.0729	-0.0002	0.0992	25.03	0.6154
0.7361	-0.2102	0.0795	-0.0818	-0.0003	0.1002	25.06	0.7148
0.7725	-0.2033	0.0857	-0.0918	-0.0003	0.0959	25.01	0.8230
0.8188	-0.1940	0.0853	-0.0990	-0.0003	0.0978	25.04	0.9234
0.8674	-0.1879	0.0938	-0.1077	-0.0001	0.0943	25.02	1.0260
0.9455	-0.1818	0.1171	-0.1153	0.0000	0.1045	25.00	1.1280
0.9955	-0.1739	0.1147	-0.1204	0.0002	0.1018	25.01	1.2288
1.0539	-0.1658	0.1071	-0.1251	0.0004	0.1031	25.00	1.3316
1.1141	-0.1587	0.0943	-0.1279	0.0004	0.1039	24.96	1.4372
1.1677	-0.1549	0.0898	-0.1299	0.0001	0.0986	25.01	1.5344

Non-Dimensional Load Data For Reverse Rotation at Coning Angle = -16 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.5923	-0.2394	-0.0307	0.0168	-0.0001	0.1000	25.08	-0.1098
0.5973	-0.2375	-0.0402	0.0275	0.0000	0.0997	25.09	-0.2039
0.6103	-0.2340	-0.0573	0.0408	0.0000	0.0989	25.11	-0.3059
0.6309	-0.2289	-0.0688	0.0537	-0.0001	0.0990	25.13	-0.4080
0.6606	-0.2232	-0.0802	0.0652	0.0004	0.0960	24.99	-0.5119
0.6832	-0.2186	-0.0934	0.0761	0.0001	0.0959	24.97	-0.6159
0.7211	-0.2116	-0.0995	0.0849	0.0003	0.0935	24.98	-0.7156
0.7615	-0.2041	-0.1110	0.0941	0.0000	0.0921	24.99	-0.8194
0.8062	-0.1962	-0.1126	0.1024	0.0002	0.0923	24.99	-0.9235
0.8512	-0.1882	-0.1150	0.1092	0.0002	0.0885	25.00	-1.0249
0.9765	-0.1732	-0.1153	0.1194	0.0010	0.0998	25.03	-1.2282
1.0269	-0.1651	-0.1030	0.1228	0.0010	0.1028	25.06	-1.3305
1.0861	-0.1571	-0.0983	0.1255	0.0009	0.1011	25.07	-1.4301
1.1505	-0.1496	-0.0897	0.1278	0.0007	0.1029	25.01	-1.5361
1.1849	-0.1415	-0.0805	0.1293	0.0009	0.0973	25.01	-1.6010

Dimensional Load Data For Forward Rotation at Coning Angle = -14 degrees

Z	M	Y	N	K	X	Vel	rpm
16.9151	91.8497	5.2258	-10.1165	-57.5285	4.6976	25.00	0.00
11.2928	123.0290	0.0786	3.9280	-0.0344	2.3001	25.04	12.28
11.4312	122.7014	0.0960	8.9864	0.0093	2.3376	25.06	25.16
11.7354	122.0151	0.1503	13.3998	0.0569	2.3491	25.10	38.01
12.1406	120.8957	0.2044	18.4284	0.0094	2.3314	25.11	50.05
12.5780	118.6282	0.3206	22.7955	0.0378	2.3139	25.07	62.58
13.1876	117.0694	0.4355	27.1750	0.1309	2.3453	25.09	75.24
14.3875	111.4742	0.5381	34.8920	0.0933	2.3566	25.05	100.17
15.2447	108.6059	0.8165	38.6667	-0.0248	2.3365	25.08	112.64
16.0480	105.7836	0.9274	41.2762	-0.1589	2.3633	25.09	125.16
17.4004	102.1944	0.5891	44.6246	0.3689	2.2787	24.97	137.36
18.2883	98.9396	0.8696	46.7059	0.5237	2.2530	25.01	149.74
19.3707	95.5726	0.9805	49.1469	0.7405	2.1289	25.01	162.44
20.4674	92.9696	1.3951	51.0095	0.8160	2.1984	25.09	174.86
21.6736	89.7246	1.7241	53.2445	0.9920	2.1857	25.11	187.30
22.7482	87.7170	2.2277	54.0285	0.9170	2.1867	25.14	199.96

Dimensional Load Data For Reverse Rotation at Coning Angle = -14 degrees

Z	M	Y	N	K	X	Vel	rpm
11.3310	121.9589	0.3203	-5.7270	-0.2235	2.3125	24.96	13.48
11.4258	121.4657	0.2838	-9.8160	-0.2088	2.3318	24.99	24.86
11.6733	120.7341	0.3294	-14.8297	-0.0979	2.3119	24.99	37.64
11.9432	119.1508	0.3452	-19.3017	-0.1105	2.3202	24.97	50.04
12.3162	117.2383	0.2642	-23.6691	-0.2539	2.3098	24.97	62.62
12.8444	115.2701	0.2588	-28.2005	-0.2119	2.2957	24.98	75.08
13.4232	112.8745	0.2181	-32.1257	-0.2409	2.2865	24.99	87.59
14.1004	109.7064	0.1501	-36.1969	-0.2681	2.2804	25.00	99.87
14.8573	106.5573	-0.0532	-38.6912	-0.3270	2.2308	24.97	112.58
15.7132	103.7593	-0.0917	-41.8296	-0.3274	2.2863	25.02	125.05
16.8773	101.4588	-0.5402	-44.1816	0.4708	2.2013	25.16	137.41
17.8160	98.0678	-0.7479	-46.1240	0.4247	2.1668	25.17	149.93
18.7922	93.5746	-0.9603	-47.3017	0.5564	2.1207	24.99	162.52
19.8740	90.4382	-1.3706	-48.6658	0.1235	2.1693	25.01	174.88
20.9859	87.8111	-1.5408	-49.5393	0.3151	2.1568	25.00	187.52
22.2284	85.0029	-1.9218	-50.9240	0.8880	2.0992	24.98	199.89

Non-Dimensional Load Data For Forward Rotation at Coning Angle = -14 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.7062	-0.1632	-0.2182	0.0180	0.1022	0.1961	25.00	0.0000
0.4700	-0.2179	-0.0033	-0.0070	0.0001	0.0957	25.04	0.1006
0.4750	-0.2170	-0.0040	-0.0159	0.0000	0.0971	25.06	0.2059
0.4861	-0.2151	-0.0062	-0.0236	-0.0001	0.0973	25.10	0.3106
0.5025	-0.2129	-0.0085	-0.0325	0.0000	0.0965	25.11	0.4088
0.5222	-0.2096	-0.0133	-0.0403	-0.0001	0.0961	25.07	0.5119
0.5467	-0.2065	-0.0181	-0.0479	-0.0002	0.0972	25.09	0.6150
0.5983	-0.1973	-0.0224	-0.0617	-0.0002	0.0980	25.05	0.8201
0.6324	-0.1917	-0.0339	-0.0683	0.0000	0.0969	25.08	0.9210
0.6652	-0.1866	-0.0384	-0.0728	0.0003	0.0980	25.09	1.0230
0.7282	-0.1820	-0.0247	-0.0795	-0.0007	0.0954	24.97	1.1281
0.7629	-0.1756	-0.0363	-0.0829	-0.0009	0.0940	25.01	1.2278
0.8081	-0.1697	-0.0409	-0.0872	-0.0013	0.0888	25.01	1.3320
0.8484	-0.1640	-0.0578	-0.0900	-0.0014	0.0911	25.09	1.4292
0.8970	-0.1580	-0.0714	-0.0938	-0.0017	0.0905	25.11	1.5297
0.9392	-0.1541	-0.0920	-0.0949	-0.0016	0.0903	25.14	1.6311

Non-Dimensional Load Data For Reverse Rotation at Coning Angle = -14 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.4746	-0.2174	-0.0134	0.0102	0.0004	0.0969	24.96	-0.1108
0.4774	-0.2160	-0.0119	0.0175	0.0004	0.0974	24.99	-0.2040
0.4878	-0.2147	-0.0138	0.0264	0.0002	0.0966	24.99	-0.3089
0.4998	-0.2122	-0.0144	0.0344	0.0002	0.0971	24.97	-0.4110
0.5155	-0.2088	-0.0111	0.0422	0.0005	0.0967	24.97	-0.5143
0.5371	-0.2051	-0.0108	0.0502	0.0004	0.0960	24.98	-0.6164
0.5609	-0.2007	-0.0091	0.0571	0.0004	0.0955	24.99	-0.7188
0.5887	-0.1949	-0.0063	0.0643	0.0005	0.0952	25.00	-0.8192
0.6218	-0.1898	0.0022	0.0689	0.0006	0.0934	24.97	-0.9246
0.6550	-0.1840	0.0038	0.0742	0.0006	0.0953	25.02	-1.0250
0.6957	-0.1780	0.0223	0.0775	-0.0008	0.0907	25.16	-1.1200
0.7338	-0.1719	0.0308	0.0808	-0.0007	0.0892	25.17	-1.2216
0.7852	-0.1664	0.0401	0.0841	-0.0010	0.0886	24.99	-1.3337
0.8291	-0.1605	0.0572	0.0864	-0.0002	0.0905	25.01	-1.4340
0.8762	-0.1560	0.0643	0.0880	-0.0006	0.0900	25.00	-1.5382
0.9295	-0.1513	0.0804	0.0906	-0.0016	0.0878	24.98	-1.6410

Dimensional Load Data For Forward Rotation at Coning Angle = -12 degrecs

Z	M	Y	N	K	X	Vel	rpm
14.3087	81.2835	5.2842	-12.3766	-57.1109	4.5197	25.00	0.00
8.3583	110.2623	0.1896	2.2631	-0.1089	2.1815	24.97	12.72
8.6333	110.0866	0.4520	5.1192	-0.0861	2.2133	25.00	25.72
8.9189	110.1129	0.7169	7.6927	-0.1455	2.2803	25.05	38.34
9.1711	109.5754	1.0842	10.0931	-0.1082	2.2620	25.05	50.36
9.4773	109.3856	1.3596	12.7620	-0.1555	2.2917	25.11	62.79
9.8292	108.6692	1.5766	15.4129	-0.1881	2.3029	25.11	75.19
10.2607	107.6331	1.9023	18.0384	-0.1760	2.2375	25.13	87.49
10.6911	105.1372	2.1789	20.8753	0.0225	2.2837	24.99	100.23
11.1400	103.4343	2.5014	23.1048	-0.0099	2.2554	25.03	112.76
11.7197	102.2202	2.7526	25.2931	-0.0937	2.2863	25.08	124.97
12.5724	100.3027	2.3433	28.2759	0.1272	2.1021	24.97	137.32
13.1078	98.0989	2.7931	29.5011	0.1604	2.1298	24.94	149.74
13.8302	96.1981	3.1221	30.4982	0.0945	2.1328	24.95	162.14
14.7132	94.7653	3.4519	31.9063	-0.0105	2.1909	24.99	174.83
15.5039	92.8985	3.8031	32.3278	-0.0062	2.1580	24.98	187.37
16.3392	91.4074	4.3895	33.3868	0.0382	2.1827	25.02	199.68

Dimensional Load Data For Reverse Rotation at Coning Angle = -12 degrees

Z	M	Y	N	K	X	Vel	rpm
8.8197	110.5350	-0.1052	-3.1781	-0.2472	2.2876	25.06	13.76
8.8960	110.3725	-0.3055	-5.0576	-0.2287	2.2876	25.08	25.05
9.0425	110.1238	-0.6272	-8.4331	-0.3344	2.2947	25.08	37.78
9.2322	109.1937	-0.7960	-11.1708	-0.2967	2.2662	25.08	49.91
9.4581	108.5460	-0.9826	-14.0813	-0.3453	2.2860	25.09	62.43
9.7221	107.2982	-1.2131	-16.9122	-0.3731	2.2755	25.09	74.98
10.1089	106.1945	-1.4714	-19.6974	-0.3134	2.2964	25.10	87.29
10.4915	104.6407	-1.6680	-21.5612	-0.3087	2.2902	25.09	99.75
11.0447	102.9572	-2.0209	-24.1030	-0.5329	2.2833	25.07	112.26
11.5690	100.5426	-2.2145	-26.0708	-0.4289	2.2815	25.06	124.97
12.2664	98.7592	-2.3151	-27.2232	-0.5222	2.0917	25.01	137.56
12.9575	97.0453	-2.5931	-28.3640	-0.5990	2.1091	25.00	150.02
13.7868	95.1280	-2.9895	-29.3604	-0.4593	2.0943	25.01	162.34
14.5120	92.6654	-3.5343	-30.3666	-0.3609	2.0779	24.98	174.87
15.2986	90.8154	-3.8744	-30.8400	-0.2571	2.0884	24.97	187.60
16.2215	89.7876	-4.2792	-31.7754	-0.1257	2.0355	25.02	199.93

Non-Dimensional Load Data For Forward Rotation at Coning Angle = -12 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.5974	-0.1444	-0.2206	0.0220	0.1015	0.1887	25.00	0.0000
0.3498	-0.1964	-0.0079	-0.0040	0.0002	0.0913	24.97	0.1045
0.3605	-0.1956	-0.0189	-0.0091	0.0002	0.0924	25.00	0.2110
0.3709	-0.1949	-0.0298	-0.0136	0.0003	0.0948	25.05	0.3139
0.3814	-0.1939	-0.0451	-0.0179	0.0002	0.0941	25.05	0.4123
0.3922	-0.1926	-0.0563	-0.0225	0.0003	0.0948	25.11	0.5128
0.4068	-0.1914	-0.0652	-0.0271	0.0003	0.0953	25.11	0.6141
0.4240	-0.1893	-0.0786	-0.0317	0.0003	0.0925	25.13	0.7140
0.4467	-0.1869	-0.0910	-0.0371	0.0000	0.0954	24.99	0.8225
0.4640	-0.1833	-0.1042	-0.0410	0.0000	0.0939	25.03	0.9239
0.4862	-0.1805	-0.1142	-0.0447	0.0002	0.0948	25.08	1.0219
0.5262	-0.1786	-0.0981	-0.0504	-0.0002	0.0880	24.97	1.1278
0.5499	-0.1751	-0.1172	-0.0527	-0.0003	0.0894	24.94	1.2313
0.5797	-0.1716	-0.1309	-0.0544	-0.0002	0.0894	24.95	1.3327
0.6148	-0.1685	-0.1442	-0.0567	0.0000	0.0915	24.99	1.4347
0.6483	-0.1653	-0.1590	-0.0575	0.0000	0.0902	24.98	1.5382
0.6811	-0.1621	-0.1830	-0.0592	-0.0001	0.0910	25.02	1.6367

Non-Dimensional Load Data For Reverse Rotation at Coning Angle = -12 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.3665	-0.1954	0.0044	0.0056	0.0004	0.0951	25.06	-0.1126
0.3691	-0.1948	0.0127	0.0089	0.0004	0.0949	25.08	-0.2048
0.3751	-0.1944	0.0260	0.0149	0.0006	0.0952	25.08	-0.3089
0.3830	-0.1928	0.0330	0.0197	0.0005	0.0940	25.08	-0.4081
0.3921	-0.1915	0.0407	0.0248	0.0006	0.0948	25.09	-0.5103
0.4030	-0.1893	0.0503	0.0298	0.0007	0.0943	25.09	-0.6129
0.4187	-0.1872	0.0609	0.0347	0.0006	0.0951	25.10	-0.7132
0.4349	-0.1846	0.0691	0.0380	0.0005	0.0949	25.09	-0.8153
0.4586	-0.1819	0.0839	0.0426	0.0009	0.0948	25.07	-0.9183
0.4807	-0.1778	0.0920	0.0461	0.0008	0.0948	25.06	-1.0227
0.5117	-0.1753	0.0966	0.0483	0.0009	0.0873	25.01	-1.1280
0.5410	-0.1724	0.1083	0.0504	0.0011	0.0881	25.00	-1.2306
0.5752	-0.1689	0.1247	0.0521	0.0008	0.0874	25.01	-1.3312
0.6069	-0.1649	0.1478	0.0540	0.0006	0.0869	24.98	-1.4356
0.6403	-0.1617	0.1621	0.0549	0.0005	0.0874	24.97	-1.5407
0.6762	-0.1593	0.1784	0.0564	0.0002	0.0848	25.02	-1.6387

Dimensional Load Data For Forward Rotation at Coning Angle = -10 degrees

Z	M	Y	N	K	X	Vel	rpm
6.2055	86.3933	0.3966	-5.5654	-10.8736	2.7945	25.00	0.00
5.8596	96.3594	0.2725	1.6845	-0.2032	2.1000	24.96	13.22
6.0614	96.8246	0.6056	2.8723	-0.1023	2.1589	25.01	25.46
6.1950	97.3793	1.0033	4.6199	-0.0712	2.1557	25.05	37.76
6.3252	97.1342	1.3485	6.0839	-0.0748	2.1822	25.07	50.37
6.5167	97.1862	1.6530	7.5265	-0.1175	2.2345	25.10	62.72
6.7677	96.8667	1.9911	9.1855	-0.0630	2.1804	25.08	75.31
6.9572	96.6810	2.2160	11.0021	-0.0341	2.2270	25.11	87.70
7.1861	96.0988	2.6245	12.0404	-0.1281	2.1873	25.14	99.92
7.4322	94.8832	2.8567	13.6313	-0.2277	2.1968	25.03	112.45
7.8528	94.3791	3.3295	15.3524	-0.1812	2.2183	25.06	124.86
8.3156	94.6500	3.6999	15.6828	0.3376	2.1226	24.99	137.18
8.7476	93.7635	4.0836	16.7924	0.4471	2.0597	24.93	149.74
9.1938	93.2358	4.4838	18.0976	0.3078	2.1582	25.01	162.12
9.6284	92.2321	4.9197	18.6912	0.3649	2.1675	25.01	174.80

Dimensional Load Data For Reverse Rotation at Coning Angle = -10 degrees

Z	M	Y	N	K	X	Vel	rpm
6.0832	96.6294	0.4906	-1.0796	-0.3130	2.1882	25.04	12.15
6.1628	96.4558	-0.8468	-2.6304	-0.3204	2.2126	25.04	25.08
6.2239	96.6380	-1.1707	-3.9299	-0.2387	2.1687	25.06	37.60
6.3885	96.5003	-1.4757	-5.9381	-0.3875	2.1829	25.08	49.98
6.4386	96.2333	-1.8132	-7.3122	-0.4150	2.2115	25.08	62.61
6.6182	95.7020	-2.1114	-9.0221	-0.3268	2.2048	25.07	74.82
6.8248	95.5251	-2.4757	-10.0910	-0.3886	2.2364	25.11	87.47
6.9890	94.5649	-2.8237	-11.7400	-0.3152	2.1703	25.09	100.10
7.2847	94.0741	-3.2480	-12.9583	-0.2700	2.2303	25.10	112.63
7.5425	93.4254	-3.6112	-13.7991	-0.2949	2.2082	25.10	124.89
8.1493	93.4543	-4.0639	-14.6713	-0.1673	2.0964	25.04	137.40
8.4969	92.6467	-4.4121	-16.0482	-0.0674	2.1329	25.00	149.79
8.9057	91.5408	-4.8893	-16.3508	-0.1507	2.1201	24.97	162.10
9.4154	90.9199	-5.3067	-17.7336	-0.1319	2.0630	25.00	174.82
9.7981	90.0644	-5.7031	-16.9511	-0.3002	2.0622	25.02	187.35
10.5857	90.4116	-6.4510	-18.4140	-0.3820	2.1028	25.01	205.72

Non-Dimensional Load Data For Forward Rotation at Coning Angle = -10 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.2591	-0.1535	-0.0166	0.0099	0.0193	0.1167	25.00	0.0000
0.2454	-0.1717	-0.0114	-0.0030	0.0004	0.0880	24.96	0.1086
0.2529	-0.1719	-0.0253	-0.0051	0.0002	0.0901	25.01	0.2088
0.2576	-0.1723	-0.0417	-0.0082	0.0001	0.0896	25.05	0.3091
0.2626	-0.1716	-0.0560	-0.0107	0.0001	0.0906	25.07	0.4120
0.2699	-0.1713	-0.0685	-0.0133	0.0002	0.0926	25.10	0.5124
0.2808	-0.1710	-0.0826	-0.0162	0.0001	0.0905	25.08	0.6158
0.2879	-0.1703	-0.0917	-0.0194	0.0001	0.0922	25.11	0.7163
0.2967	-0.1688	-0.1084	-0.0212	0.0002	0.0903	25.14	0.8151
0.3096	-0.1682	-0.1190	-0.0242	0.0004	0.0915	25.03	0.9213
0.3263	-0.1669	-0.1383	-0.0271	0.0003	0.0922	25.06	1.0218
0.3475	-0.1683	-0.1546	-0.0279	-0.0006	0.0887	24.99	1.1257
0.3673	-0.1675	-0.1715	-0.0300	-0.0008	0.0865	24.93	1.2318
0.3835	-0.1655	-0.1871	-0.0321	-0.0005	0.0900	25.01	1.3293
0.4017	-0.1637	-0.2052	-0.0332	-0.0006	0.0904	25.01	1.4333

Non-Dimensional Load Data For Reverse Rotation at Coning Angle = -10 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.2532	-0.1711	0.0204	0.0019	0.0006	0.0911	25.04	-0.0995
0.2565	-0.1708	0.0352	0.0047	0.0006	0.0921	25.04	-0.2054
0.2536	-0.1709	0.0486	0.0069	0.0004	0.0901	25.06	-0.3077
0.2650	-0.1704	0.0612	0.0105	0.0007	0.0906	25.08	-0.4087
0.2671	-0.1699	0.0752	0.0129	0.0007	0.0917	25.08	-0.5120
0.2748	-0.1691	0.0877	0.0159	0.0006	0.0915	25.07	-0.6120
0.2825	-0.1682	0.1025	0.0178	0.0007	0.0926	25.11	-0.7144
0.2897	-0.1668	0.1170	0.0207	0.0006	0.0900	25.09	-0.8182
0.3017	-0.1658	0.1345	0.0228	0.0005	0.0924	25.10	-0.9202
0.3124	-0.1647	0.1496	0.0243	0.0005	0.0915	25.10	-1.0204
0.3392	-0.1655	0.1691	0.0260	0.0003	0.0872	25.04	-1.1253
0.3548	-0.1646	0.1842	0.0285	0.0001	0.0891	25.00	-1.2287
0.3727	-0.1630	0.2046	0.0291	0.0003	0.0887	24.97	-1.3313
0.3931	-0.1615	0.2216	0.0315	0.0002	0.0861	25.00	-1.4341
0.4084	-0.1598	0.2377	0.0301	0.0005	0.0860	25.02	-1.5356
0.4416	-0.1605	0.2691	0.0327	0.0007	0.0877	25.01	-1.6869

Dimensional Load Data For Forward Rotation at Coning Angle = -8 degrees

Z	M	Y	N	K	X	Vel	rpm
9.4352	57.1550	4.9845	-11.5938	-52.3509	4.3899	25.00	0.00
4.3229	83.4408	0.1850	0.5115	-0.2616	2.1685	25.07	12.91
4.2526	83.6316	0.5390	0.7814	-0.1686	2.1386	25.10	24.98
4.2789	84.0701	0.8579	1.4587	-0.1569	2.1191	25.12	37.38
4.3931	84.5539	1.2653	1.6941	-0.1583	2.1713	25.15	50.12
4.5240	84.8363	1.6896	2.8351	-0.0705	2.1823	25.17	62.76
4.5910	85.3396	1.9629	3.3785	-0.0781	2.1726	25.20	74.96
4.6623	85.4735	2.3443	4.1171	-0.1624	2.1453	25.20	87.37
4.8724	86.0754	2.7016	4.7948	-0.1595	2.1865	25.22	100.22
5.0407	86.4049	3.1307	5.7709	0.1056	2.1694	25.21	112.76
5.1443	86.5344	3.4897	6.1712	0.9355	2.1711	25.22	125.07
5.2203	84.9883	3.4252	7.2498	-0.1273	2.1867	25.02	137.40
5.4800	85.0599	3.7778	7.8492	-0.0519	2.1853	25.03	149.57
5.7448	85.9076	4.2459	7.7772	0.0332	2.2442	25.04	162.31
6.0440	86.4622	4.7772	8.3651	-0.0463	2.3352	25.08	174.80
6.3231	87.2060	5.2282	8.1483	-0.0104	2.3437	25.11	187.37
6.6164	87.0547	5.5534	8.3809	-0.0653	2.3238	25.03	199.90

Dimensional Load Data For Reverse Rotation at Coning Angle = -8 degrees

Z	M	Y	N	K	X	Vel	rpm
4.4446	83.4904	-0.2111	-0.6528	0.2410	2.1790	25.07	12.81
4.4130	83.6976	-0.5890	-1.2777	0.3028	2.1611	25.10	24.54
4.3871	83.7214	-0.9374	-1.2279	0.4050	2.1346	25.10	37.44
4.4301	83.8669	-1.3217	-2.0508	0.2548	2.1724	25.12	50.01
4.5225	84.0876	-1.6669	-2.7162	0.1667	2.1668	25.14	62.42
4.5729	84.2475	-2.0418	-3.3400	0.5909	2.1748	25.15	75.20
4.7741	84.3802	-2.5579	-4.5634	0.6838	2.1515	25.15	99.88
4.9086	84.1318	-2.9666	-5.4887	0.1401	2.1124	25.11	112.52
5.1287	84.5187	-3.2995	-5.9017	0.3465	2.1530	25.16	124.99
4.9777	84.2928	-3.8363	-5.9251	-0.2395	2.3073	25.06	137.41
5.2649	84.9165	-4.1739	-5.7693	-0.3123	2.3367	25.08	149.84
5.5716	84.9259	-4.5815	-6.9081	-0.3587	2.3632	25.06	162.25
5.8953	85.2759	-4.9844	-7.4022	-0.6296	2.3200	25.07	174.83
6.0652	85.2411	-5.3354	-6.8065	-0.4548	2.4000	25.09	187.33
6.3784	85.6646	-5.7344	-6.5689	-0.5786	2.4024	25.06	199.76

Non-Dimensional Load Data For Forward Rotation at Coning Angle = -8 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.3939	-0.1015	-0.2081	0.0206	0.0930	0.1833	25.00	0.0000
0.1795	-0.1474	-0.0077	-0.0009	0.0005	0.0900	25.07	0.1056
0.1761	-0.1474	-0.0223	-0.0014	0.0003	0.0886	25.10	0.2041
0.1769	-0.1479	-0.0355	-0.0026	0.0003	0.0876	25.12	0.3052
0.1812	-0.1484	-0.0522	-0.0030	0.0003	0.0896	25.15	0.4087
0.1863	-0.1487	-0.0696	-0.0050	0.0001	0.0899	25.17	0.5113
0.1886	-0.1492	-0.0807	-0.0059	0.0001	0.0893	25.20	0.6100
0.1916	-0.1495	-0.0963	-0.0072	0.0003	0.0882	25.20	0.7110
0.1999	-0.1503	-0.1108	-0.0084	0.0003	0.0897	25.22	0.8149
0.2070	-0.1510	-0.1285	-0.0101	-0.0002	0.0891	25.21	0.9173
0.2110	-0.1511	-0.1432	-0.0108	-0.0016	0.0891	25.22	1.0170
0.2176	-0.1508	-0.1428	-0.0129	0.0002	0.0912	25.02	1.1262
0.2282	-0.1508	-0.1573	-0.0139	0.0001	0.0910	25.03	1.2255
0.2391	-0.1521	-0.1767	-0.0138	-0.0001	0.0934	25.04	1.3293
0.2507	-0.1526	-0.1982	-0.0148	0.0001	0.0969	25.08	1.4293
0.2617	-0.1536	-0.2164	-0.0144	0.0000	0.0970	25.11	1.5303
0.2756	-0.1543	-0.2313	-0.0149	0.0001	0.0968	25.03	1.6378

Non-Dimensional Load Data For Reverse Rotation at Coning Angle = -8 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.1845	-0.1475	0.0088	0.0012	-0.0004	0.0905	25.07	-0.1048
0.1828	-0.1475	0.0244	0.0023	-0.0005	0.0895	25.10	-0.2005
0.1817	-0.1476	0.0388	0.0022	-0.0007	0.0884	25.10	-0.3059
0.1832	-0.1476	0.0547	0.0036	-0.0004	0.0898	25.12	-0.4083
0.1867	-0.1477	0.0688	0.0048	-0.0003	0.0895	25.14	-0.5092
0.1887	-0.1479	0.0842	0.0059	-0.0010	0.0897	25.15	-0.6132
0.1970	-0.1481	0.1055	0.0080	-0.0012	0.0888	25.15	-0.8144
0.2031	-0.1482	0.1228	0.0097	-0.0002	0.0874	25.11	-0.9190
0.2114	-0.1483	0.1360	0.0104	-0.0006	0.0888	25.16	-1.0188
0.2068	-0.1490	0.1594	0.0105	0.0004	0.0959	25.06	-1.1245
0.2184	-0.1499	0.1732	0.0102	0.0006	0.0969	25.08	-1.2252
0.2315	-0.1502	0.1904	0.0122	0.0006	0.0982	25.06	-1.3278
0.2448	-0.1507	0.2069	0.0131	0.0011	0.0963	25.07	-1.4301
0.2514	-0.1504	0.2212	0.0120	0.0008	0.0995	25.09	-1.5312
0.2650	-0.1515	0.2383	0.0116	0.0010	0.0998	25.06	-1.6347

Dimensional Load Data For Forward Rotation at Coning Angle = -6 degrees

Z	M	Y	N	K	X	Vel	rpm
3.3706	58.6089	0.7061	-1.4108	-5.8439	2.3706	25.00	0.00
1.2245	66.5119	-0.5518	-13.7275	17.2314	1.0871	24.89	12.77
1.2949	66.8878	0.0563	-13.3997	17.2148	1.1426	24.89	37.53
1.3160	67.5502	0.6607	-12.5771	17.3106	1.1662	24.92	62.76
1.4173	68.3982	1.2347	-12.1388	17.4307	1.1695	24.93	87.57
1.5513	69.2811	1.8569	-11.1774	17.5997	1.2002	24.97	112.92
1.8409	70.5246	2.3548	-10.5271	17.6908	1.1656	24.94	137.62
1.9617	71.8060	2.9297	-10.5548	16.8077	1.2331	24.97	162.35
1.7047	74.2334	3.3572	-9.5026	16.4589	1.1826	25.13	187.93

Dimensional Load Data For Reverse Rotation at Coning Angle = -6 degrees

Z	M	Y	N	K	X	Vel	rpm
1.3032	66.8912	-1.4310	-14.4903	17.1483	1.1853	25.04	25.11
1.3286	67.2275	-1.9627	-15.2245	17.1664	1.1931	25.07	49.98
1.4191	67.9671	-2.5707	-15.6162	17.1023	1.2390	25.10	75.22
1.4845	68.7929	-3.1675	-16.0597	17.0573	1.1722	25.11	100.15
1.5935	69.5809	-3.7773	-16.6974	16.9036	1.1595	25.14	124.89
1.6888	70.7136	-4.2820	-16.9680	16.5758	1.1162	25.00	149.91
1.8821	71.8867	-4.7882	-17.0022	16.6141	1.0809	24.99	175.01
2.0615	73.6186	-5.4481	-17.3560	16.3217	1.1097	25.00	200.00

Non-Dimensional Load Data For Forward Rotation at Coning Angle = -6 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.1407	-0.1041	-0.0295	-0.0225	0.0104	0.0990	25.00	0.0000
0.0516	-0.1192	0.0232	-0.0004	-0.0309	0.0458	24.89	0.1052
0.0545	-0.1199	-0.0024	-0.0010	-0.0309	0.0481	24.89	0.3092
0.0553	-0.1208	-0.0278	-0.0025	-0.0310	0.0490	24.92	0.5165
0.0595	-0.1222	-0.0518	-0.0033	-0.0311	0.0491	24.93	0.7204
0.0649	-0.1234	-0.0777	-0.0051	-0.0313	0.0502	24.97	0.9274
0.0772	-0.1259	-0.0988	-0.0062	-0.0316	0.0489	24.94	1.1316
0.0821	-0.1279	-0.1226	-0.0062	-0.0299	0.0516	24.97	1.3334
0.0704	-0.1305	-0.1387	-0.0083	-0.0289	0.0489	25.13	1.5336

Non-Dimensional Load Data For Reverse Rotation at Coning Angle = -6 degrees

Z'	M'	Y'		K'	X'	Vel	rpm'
0.0542	-0.1185	0.0596	0.0007	-0.0304	0.0493	25.04	-0.2056
0.0552	-0.1188	0.0815	0.0019	-0.0303	0.0495	25.07	-0.4088
0.0588	-0.1198	0.1065	0.0025	-0.0301	0.0513	25.10	-0.6146
0.0614	-0.1212	0.1311	0.0033	-0.0300	0.0485	25.11	-0.8179
0.0658	-0.1222	0.1560	0.0043	-0.0297	0.0479	25.14	-1.0188
0.0705	-0.1256	0.1788	0.0051	-0.0294	0.0466	25.00	-1.2297
0.0786	-0.1278	0.2001	0.0052	-0.0295	0.0452	24.99	-1.4362
0.0861	-0.1308	0.2275	0.0058	-0.0290	0.0463	25.00	-1.6406

Dimensional Load Data For Forward Rotation at Coning Angle = -4 degrees

Z	M	Y	N	K	X	Vel	rpm
6.6033	21.8781	4.8999	-10.6082	-48.9253	4.0773	25.00	0.00
1.0188	46.8370	0.0662	-0.0668	-0.0928	2.0900	25.14	13.08
1.0249	47.1501	0.2671	-0.1688	-0.0878	2.1016	25.17	24.91
1.0532	47.5289	0.4857	-0.4030	-0.0633	2.1352	25.22	37.48
1.1028	47.7068	0.7332	-0.3068	-0.0648	2.1206	25.22	49.95
1.0858	47.2894	0.9050	-0.1000	-0.1812	2.1367	25.11	62.34
1.1032	47.9866	0.9931	-0.0498	0.1649	2.1274	25.16	74.93
1.1641	48.3090	1.2546	0.0571	0.2760	2.1186	25.17	87.71
1.3973	49.3287	1.8388	-0.4800	0.2891	2.1588	25.19	112.39
1.5279	49.7502	1.9803	-0.2050	0.0983	2.1484	25.22	124.91
1.8745	48.6646	2.4970	-1.4754	-5.4609	2.3410	25.09	137.35
1.8613	49.5713	2.6621	-1.6115	-4.8565	2.2816	25.09	149.71
1.8221	50.4822	2.7740	-1.5004	-4.9652	2.2806	25.12	161.95
1.8528	51.3061	2.8576	-1.8305	-5.0175	2.3110	25.16	174.88
1.8917	52.1875	3.0165	-2.0076	-5.6205	2.3402	25.20	187.15
1.8457	52.7793	3.1154	-1.6996	-4.9073	2.2823	25.05	199.58

Dimensional Load Data For Reverse Rotation at Coning Angle = -4 degrees

Z	M	Y	N	K	X	Vel	rpm
0.8149	46.0902	-0.1991	-0.2706	0.2232	2.0459	25.08	11.82
0.8386	46.1109	-0.3884	-0.1217	-0.2085	2.0567	25.08	25.17
0.7748	46.2182	-0.5551	-0.0460	-0.0286	2.0270	25.09	37.76
0.7691	46.2011	-0.7643	-0.2813	0.1402	2.0619	25.09	49.96
0.7683	46.3760	-1.0457	-0.3070	0.1887	2.0298	25.08	62.75
0.7407	46.8818	-1.2172	-0.1285	0.3437	2.0322	25.08	74.95
0.7830	47.3522	-1.4549	-0.1431	0.1112	2.0305	25.09	87.67
0.7596	47.7398	-1.6389	0.0709	-0.0096	2.0429	25.08	100.00
0.7871	48.2062	-1.8601	0.0133	-0.2821	2.0610	25.09	112.68
0.8659	48.1052	-1.8920	0.6496	-0.4711	2.0777	25.11	124.98
1.8441	47.2935	-0.9025	-2.0586	-4.9425	2.1911	25.07	137.31
1.8670	47.6085	-1.0969	-1.7408	-6.0073	2.2055	25.12	149.73
1.7615	49.0170	-1.4213	-1.6957	-5.0839	2.2165	25.13	162.16
1.5191	49.3373	-1.6941	-0.8817	-4.6756	2.2278	25.14	174.65
1.5557	50.9231	-2.0189	-0.0913	-4.2505	2.3031	25.16	187.10
1.5392	51.7429	-2.1647	0.0402	-4.1726	2.3192	25.18	199.68

Non-Dimensional Load Data For Forward Rotation at Coning Angle = -4 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.2757	-0.0389	-0.2046	0.0188	0.0869	0.1702	25.00	0.0000
0.0421	-0.0823	-0.0027	0.0001	0.0002	0.0863	25.14	0.1067
0.0422	-0.0826	-0.0110	0.0003	0.0002	0.0866	25.17	0.2030
0.0432	-0.0830	-0.0199	0.0007	0.0001	0.0876	25.22	0.3048
0.0452	-0.0833	-0.0301	0.0005	0.0001	0.0870	25.22	0.4062
0.0449	-0.0833	-0.0375	0.0002	0.0003	0.0884	25.11	0.5091
0.0455	-0.0842	-0.0409	0.0001	-0.0003	0.0877	25.16	0.6107
0.0479	-0.0847	-0.0517	-0.0001	-0.0005	0.0873	25.17	0.7146
0.0575	-0.0863	-0.0756	0.0008	-0.0005	0.0888	25.19	0.9150
0.0627	-0.0869	-0.0812	0.0004	-0.0002	0.0881	25.22	1.0157
0.0777	-0.0858	-0.1035	0.0026	0.0096	0.0970	25.09	1.1226
0.0772	-0.0874	-0.1103	0.0028	0.0086	0.0946	25.09	1.2237
0.0753	-0.0888	-0.1147	0.0026	0.0087	0.0943	25.12	1.3221
0.0764	-0.0900	-0.1178	0.0032	0.0088	0.0953	25.16	1.4254
0.0777	-0.0913	-0.1240	0.0035	0.0098	0.0962	25.20	1.5230
0.0768	-0.0934	-0.1296	0.0030	0.0087	0.0949	25.05	1.6339

Non-Dimensional Load Data For Reverse Rotation at Coning Angle = -4 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.0338	-0.0814	0.0083	0.0005	-0.0004	0.0849	25.08	-0.0967
0.0348	-0.0814	0.0161	0.0002	0.0004	0.0853	25.08	-0.2058
0.0321	-0.0815	0.0230	0.0001	0.0001	0.0840	25.09	-0.3086
0.0319	-0.0815	0.0317	0.0005	-0.0002	0.0855	25.09	-0.4084
0.0319	-0.0819	0.0434	0.0005	-0.0003	0.0842	25.08	-0.5131
0.0307	-0.0828	0.0505	0.0002	-0.0006	0.0843	25.08	-0.6129
0.0325	-0.0835	0.0603	0.0003	-0.0002	0.0842	25.09	-0.7166
0.0315	-0.0843	0.0680	-0.0001	0.0000	0.0848	25.08	-0.8177
0.0326	-0.0850	0.0771	0.0000	0.0005	0.0854	25.09	-0.9210
0.0358	-0.0847	0.0783	-0.0011	0.0008	0.0860	25.11	-1.0207
0.0766	-0.0836	0.0375	0.0036	0.0087	0.0910	25.07	-1.1232
0.0772	-0.0838	0.0454	0.0031	0.0106	0.0912	25.12	-1.2224
0.0728	-0.0862	0.0587	0.0030	0.0089	0.0916	25.13	-1.3233
0.0627	-0.0867	0.0699	0.0015	0.0082	0.0920	25.14	-1.4247
0.0641	-0.0893	0.0832	0.0002	0.0075	0.0949	25.16	-1.5250
0.0633	-0.0906	0.0891	-0.0001	0.0073	0.0954	25.18	-1.6263

Dimensional Load Data For Forward Rotation at Coning Angle = -2 degrees

Z	M	Y	N	K	X	Vel	rpm
1.6321	15.2077	0.7600	-3.4971	-9.9625	2.5414	25.00	0.00
0.3472	26.1328	-0.1432	-0.1172	-0.2192	1.9423	24.95	12.46
0.3168	26.4212	0.1510	-0.4789	-0.0796	2.0012	24.90	37.44
0.3924	26.7632	0.3464	-1.1906	-0.0768	2.0137	24.93	62.45
0.4482	27.0151	0.5305	-1.4774	0.0254	2.0388	24.96	87.15
0.5199	27.9819	0.6848	-2.2622	0.0137	2.0189	24.98	112.31
0.3977	28.3817	0.4792	-3.1299	0.2852	1.8939	24.99	137.40
0.3936	28.8609	0.5965	-2.6061	0.4909	1.8232	24.97	162.70
0.5818	30.0543	0.4760	-3.8705	0.2130	2.0006	25.03	187.46

Dimensional Load Data For Reverse Rotation at Coning Angle = -2 degrees

Z	M	Y	N	K	X	Vel	rpm
0.5098	26.3594	-0.1380	0.1600	-0.1521	2.0486	25.01	25.44
0.4784	26.6496	-0.2996	0.7314	-0.1600	2.0323	25.04	50.15
0.5096	26.5273	-0.4183	1.0829	-0.1797	2.0349	25.04	74.98
0.5610	26.7967	-0.5148	1.4681	-0.1861	2.0566	25.04	99.98
0.6519	27.0892	-0.6558	2.3788	-0.2020	2.0763	25.09	125.33
0.5167	27.3611	-0.9612	2.9323	0.0067	1.8804	25.02	150.04
0.5191	28.1504	-0.9574	3.9547	-0.0252	1.9053	25.00	175.22
0.4413	26.4281	-1.0711	3.2839	-3.6842	2.2360	24.96	196.89

Non-Dimensional Load Data For Forward Rotation at Coning Angle = -2 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.0681	-0.0270	-0.0317	0.0062	0.0177	0.1061	25.00	0.0000
0.0146	-0.0466	0.0060	0.0002	0.0004	0.0814	24.95	0.1024
0.0133	-0.0473	-0.0064	0.0009	0.0001	0.0842	24.90	0.3084
0.0165	-0.0478	-0.0145	0.0021	0.0001	0.0845	24.93	0.5137
0.0188	-0.0482	-0.0222	0.0026	0.0000	0.0854	24.96	0.7160
0.0217	-0.0498	-0.0286	0.0040	0.0000	0.0844	24.98	0.9220
0.0166	-0.0505	-0.0200	0.0056	-0.0005	0.0791	24.99	1.1275
0.0165	-0.0514	-0.0250	0.0046	-0.0009	0.0763	24.97	1.3362
0.0242	-0.0533	-0.0198	0.0069	-0.0004	0.0833	25.03	1.5359

Non-Dimensional Load Data For Reverse Rotation at Coning Angle = -2 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.0213	-0.0468	0.0058	-0.0003	0.0003	0.0855	25.01	-0.2086
0.0199	-0.0472	0.0125	-0.0013	0.0003	0.0846	25.04	-0.4107
0.0212	-0.0470	0.0174	-0.0019	0.0003	0.0847	25.04	-0.6141
0.0233	-0.0475	0.0214	-0.0026	0.0003	0.0856	25.04	-0.8188
0.0270	-0.0478	0.0272	-0.0042	0.0004	0.0861	25.09	-1.0244
0.0215	-0.0485	0.0401	-0.0052	0.0000	0.0784	25.02	-1.2298
0.0217	-0.0500	0.0400	-0.0070	0.0000	0.0795	25.00	-1.4373
0.0185	-0.0471	0.0449	-0.0059	0.0066	0.0937	24.96	-1.6177

Dimensional Load Data For Forward Rotation at Coning Angle = 0 degrees

Z	M	Y	N	K	X	Vel	rpm
0.7967	-12.0599	1.7989	-4.9190	-19.4488	2.9345	25.00	0.00
-0.2419	4.1745	-0.1209	-0.4770	-0.0106	2.0840	24.95	14.15
-0.2700	4.1757	-0.1425	-0.9813	-0.0912	2.0949	25.00	25.87
-0.3088	4.0453	-0.1183	-0.9937	-0.0083	2.1183	25.03	37.61
-0.6246	3.6192	-0.2008	-1.3193	0.0731	2.0433	25.03	50.29
-0.6331	3.7964	-0.2185	-1.5685	0.0414	2.0198	25.03	62.35
-0.6643	3.5874	-0.2595	-1.6139	0.1016	2.0506	25.07	74.93
-0.6369	3.3831	-0.3340	-1.8938	0.0786	1.9954	25.02	87.42
-0.6362	3.3507	-0.4042	-2.5624	0.0083	2.0038	25.04	99.98
-0.4331	3.3197	-0.4630	-2.7512	-0.0796	1.9964	25.00	112.31
-0.3547	3.5686	-0.5550	-3.0694	-0.0129	2.0091	24.98	125.05
-0.7402	2.8022	-0.8791	-2.9461	-0.0105	1.9769	25.01	149.74

Dimensional Load Data For Reverse Rotation at Coning Angle = 0 degrees

Z	M	Y	N	K	X	Vel	rpm
-0.6666	3.4557	0.0207	-0.2216	-0.2494	1.9997	24.99	15.72
-0.6633	3.9024	0.0797	0.1229	-0.2050	2.0109	25.01	25.40
-0.6602	3.6458	0.1694	0.2179	-0.0342	2.0076	25.02	37.62
-0.6202	3.5016	0.2337	0.7122	-0.2158	2.0150	25.02	50.10
-0.6449	3.3906	0.2983	0.8687	-0.2396	2.0087	25.02	62.78
-0.7197	3.3341	0.3217	1.2053	-0.1415	2.0188	25.02	74.92
-0.8042	2.9214	0.3385	1.4328	-0.1719	1.9386	24.96	87.18
-0.8041	2.3766	0.4588	2.2018	-0.2452	2.0205	24.98	100.16
-0.7701	1.7791	0.5336	2.2009	-0.2205	1.9473	24.96	112.47
-0.8630	2.3330	0.6099	2.7185	-0.0997	1.9133	24.97	125.00

Non-Dimensional Load Data For Forward Rotation at Coning Angle = 0 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
0.0333	0.0214	-0.0751	0.0087	0.0346	0.1225	25.00	0.0000
-0.0101	-0.0074	0.0051	0.0009	0.0000	0.0874	24.95	0.1163
-0.0113	-0.0074	0.0059	0.0017	0.0002	0.0875	25.00	0.2122
-0.0129	-0.0072	0.0049	0.0018	0.0000	0.0882	25.03	0.3081
-0.0260	-0.0064	0.0084	0.0023	-0.0001	0.0851	25.03	0.4120
-0.0264	-0.0067	0.0091	0.0028	-0.0001	0.0841	25.03	0.5108
-0.0276	-0.0063	0.0108	0.0029	-0.0002	0.0851	25.07	0.6129
-0.0265	-0.0060	0.0139	0.0034	-0.0001	0.0832	25.02	0.7165
-0.0265	-0.0059	0.0168	0.0045	0.0000	0.0834	25.04	0.8188
-0.0181	-0.0059	0.0193	0.0049	0.0001	0.0834	25.00	0.9213
-0.0148	-0.0064	0.0232	0.0055	0.0000	0.0840	24.98	1.0266
-0.0309	-0.0050	0.0367	0.0052	0.0000	0.0825	25.01	1.2278

Non-Dimensional Load Data For Reverse Rotation at Coning Angle = 0 degrees

Z'	M'	Y'	N'	K'	X'	Vel	rpm'
-0.0279	-0.0061	-0.0009	0.0004	0.0004	0.0836	24.99	-0.1290
-0.0277	-0.0069	-0.0033	-0.0002	0.0004	0.0839	25.01	-0.2083
-0.0275	-0.0065	-0.0071	-0.0004	0.0001	0.0837	25.02	-0.3084
-0.0259	-0.0062	-0.0097	-0.0013	0.0004	0.0840	25.02	-0.4106
-0.0269	-0.0060	-0.0124	-0.0015	0.0004	0.0837	25.02	-0.5146
-0.0300	-0.0059	-0.0134	-0.0021	0.0003	0.0842	25.02	-0.6141
-0.0337	-0.0052	-0.0142	-0.0026	0.0003	0.0812	24.96	-0.7163
-0.0336	-0.0042	-0.0192	-0.0039	0.0004	0.0845	24.98	-0.8223
-0.0323	-0.0032	-0.0223	-0.0039	0.0004	0.0816	24.96	-0.9241
-0.0361	-0.0042	-0.0255	-0.0048	0.0002	0.0801	24.97	-1.0266

Appendix C

Test Data: Flow Field Mapping

The data included in this Appendix is a sample (for α_c=-20°) of the output for:

- The data gathering in LDV/Tunnel Space
- The translation into Body Space
- The PostScript output file which drives a graphics device

This is a summary of several lines from the output of SUBVEL:

```
Alpha = -20 deg   75.0 rpm test on 02-20-1990 at 1556
Posit   1    -83.566      .000   -139.700
   Alpha     Uo        Wo
    .000  -26.485     .312
   2.000  -26.357     .132
   4.000  -26.159     .078
   6.000  -26.098     .130
   8.000  -25.966     .117
  10.000  -26.621     .129
  12.000  -26.776     .433
  14.000  -26.591     .154
  16.000  -26.183     .133
  18.000  -26.375     .317
  20.000  -26.114     .246
  22.000  -26.392     .413
  24.000  -26.364     .324
  26.000  -26.437     .562
  28.000  -26.426     .536
  30.000  -26.542     .371
  32.000  -26.434     .478
  34.000   26.618     .404
  36.000  -26.468     .738
  38.000  -26.454     .646
  40.000  -26.513     .644
  42.000  -26.437     .544
  44.000  -26.587     .758
  46.000  -26.878     .618
  48.000  -27.005     .881
.........
 348.000  -26.488    -.053
 350.000  -26.289     .275
 352.000  -25.748     .041
 354.000  -26.085     .022
 356.000  -26.037     .045
 358.000  -26.429     .153
Posit   2    -83.566      .000   -132.715
   Alpha     Uo        Wo
    .000  -26.222    -.057
   2.000  -25.929     .005
   4.000  -26.183    -.040
   6.000  -26.190     .009
   8.000  -26.027     .009
  10.000  -26.205    -.003
..... etc.
```

This is a summary of several lines from the output of PERTURB:

Coning Angle = -20 at 75.0 rpm on 02-20-1990 at 1556

X	Y	Z	U	V	W
-126.307	.000	-102.694	.107	.000	.293
-126.277	-4.875	-102.614	.045	.005	.124
-126.190	-9.745	-102.374	.027	.005	.073
-126.045	-14.603	-101.975	.044	.014	.121
-125.842	-19.442	-101.416	.040	.016	.109
-125.581	-24.259	-100.699	.043	.022	.119
-125.262	-29.045	-99.825	.145	.090	.398
-124.887	-33.796	-98.794	.051	.037	.140
-124.456	-38.507	-97.608	.044	.037	.120
-123.968	-43.170	-96.269	.103	.098	.283
-123.425	-47.780	-94.777	.079	.084	.217
-122.827	-52.333	-93.135	.131	.155	.360
-122.176	-56.821	-91.344	.101	.132	.278
-121.471	-61.240	-89.408	.173	.246	.475
-120.714	-65.585	-87.328	.162	.252	.445
-119.905	-69.850	-85.106	.110	.185	.302
-119.046	-74.030	-82.746	.139	.253	.381
-118.138	-78.119	-80.251	.115	.226	.315
-117.181	-82.114	-77.622	.204	.434	.561
-116.178	-86.008	-74.865	.174	.398	.478
-115.128	-89.797	-71.981	.169	.414	.464
-114.034	-93.478	-68.975	.138	.364	.380
-112.897	-97.044	-65.850	.186	.527	.512
-111.717	-100.492	-62.610	.147	.445	.403
-110.498	-103.817	-59.259	.202	.655	.554
-109.239	-107.016	-55.801	.176	.614	.484
-107.943	-110.085	-52.240	.152	.567	.417
-106.611	-113.020	-48.580	.126	.506	.346
-105.245	-115.817	-44.827	.161	.697	.442
-103.846	-118.472	-40.984	.150	.704	.413
-102.416	-120.984	-37.056	.159	.805	.436
-100.958	-123.348	-33.049	.150	.826	.413
-99.472	-125.562	-28.966	.131	.785	.360
-97.960	-127.622	-24.813	.115	.758	.317
-96.425	-129.528	-20.595	.129	.936	.356
-94.868	-131.275	-16.317	.111	.894	.306
-93.291	-132.863	-11.985	.091	.817	.249
-91.696	-134.288	-7.603	.074	.757	.204
-90.085	-135.550	-3.177	.075	.880	.206
-88.460	-136.647	1.288	.063	.860	.172
-86.823	-137.578	5.786	.057	.953	.158
-85.176	-138.340	10.311	.047	.980	.129
-83.521	-138.935	14.859	.033	.931	.092

This is an abbreviated version of a PostScript file which is the output of VECTORS:

```
%!PS-Adobe-1.0
%%BoundingBox: 0 0 612 792
%%Title: 75520.ps
%%Pages: 1
%%DocumentFonts: Helvetica
%%EndComments
/m {moveto} def
/l {lineto} def
/s {stroke} def
/f {fill} def
/n {newpath} def
/arrow {newpath
    0 0 moveto
    1 0 lineto
    1 0 moveto
    0.75 0.10 lineto
    1 0 moveto
    0.75 -0.10 lineto} def
0.072 setlinewidth
2 setlinejoin
/Helvetica findfont
9 scalefont setfont
%%EndProlog
%%Page: 1 1
306 396 translate
1.1339 -1.1339 scale
gsave
 2.000 2.000 scale
 0 -88.515 translate
gsave
n
    .392 setlinewidth
    .000  -42.751 translate
  -5.398 rotate
    .255    .255 scale
arrow s
grestore
gsave
n
    .494 setlinewidth
  -4.875  -42.671 translate
 -41.399 rotate
    .203    .203 scale
arrow s
grestore
gsave
n
    .542 setlinewidth
  -9.745  -42.432 translate
 260.334 rotate
    .185    .185 scale
arrow s
grestore
gsave
n
    .376 setlinewidth
 -14.603  -42.032 translate
 186.697 rotate
    .266    .266 scale
arrow s
grestore
gsave
n

.....

0.72 setlinewidth
/Helvetica findfont 9 scalefont setfont
n
-203.2 -203.2 m
-203.2 203.2 l
203.2 203.2 l s
1 -1 scale
n
  -210.   200. m
  -203.   200.  l s
n
```

```
 -235.  200. m ( -11  ) show
n
 -210.  180. m
 -203.  180.  l s
n
 -235.  180. m (  -1  ) show
n
 -210.  160. m
 -203.  160.  l s
n

.....

n
  200.  -210. m
  200.  -203.  l s
n
  190.  -220. m ( 100  ) show
n
/Helvetica findfont 12 scalefont setfont
-20 -240 m
(Y  \(in mm\)) show
n
/Helvetica findfont 16 scalefont setfont
-70 260 m
(Cross Flow Velocities) show
n
/Helvetica findfont 10 scalefont setfont
-115. 245. m
(Coning Angle = -20 degrees.  75 rpm, at Xo = -258.8) show
n
/Helvetica findfont 12 scalefont setfont
-240 0 m
90 rotate
(Z  \(in mm\)) show
grestore
showpage
%%Trailer
%%EOF
```

Appendix D

Computer Programs

The following programs were written in Microsoft FORTRAN and compiled for use on an IBM PC XT, AT or PS/2.

```
c       ***********************************************************
c       *                                                         *
c       *              SUBVEL.FOR                                 *
c       *                                                         *
c       *                 by                                      *
c       *                                                         *
c       *              Tom Eccles                                 *
c       *                 and                                     *
c       *              Buddy Duncan                               *
c       *                                                         *
c       *              February 1990                              *
c       *                                                         *
c       ***********************************************************

c       This program takes tunnel coordinates in mm from a data
c       file, converts to laser table coordinates, positions the
c       laser at those coordinates and measures the velocity there
c       for 1000 counts and writes the data to an output file
c       which records velocity and rotational position.

        program subvel

$DEBUG
        character*1 stopgo
        integer alpha
        integer*2 ispeed,ibase96
        real rpm
        dimension vx(360),vz(360), phi(360)
        character*20 infile,outfile

c       Setup all devices
        ibase96=784
        call setp96(ibase96)
        call lset
        call setup

c       take care of input and output files
        write(*,'(a\)')' Enter the input data file ==>'
        read(*,'(a20)') infile
        write(*,'(a\)')' Enter the output data file ==>'
        read(*,'(a20)') outfile
        open(unit=1,file=infile,status='old')
        open(unit=3,file=outfile)
        call gettim(ihr,imin,isec,i100th)
        call getdat(iyr,imon,iday)
        read(1,*)alpha,rpm
        write(*,4999)alpha,rpm
        pause ' SET THE ABOVE VALUES THEN HIT RETURN'
        write(3,5000) alpha, rpm, imon, iday, iyr, ihr, imin

c       Set refraction value to account for Y correction
        snell=1/1.34569

c       Move the LDV Table to each sample point and measure velocities
c     and rotation angle (phi). Write the data to the output file
```

```
      nposit=1
900   continue
      read(1,*,end=1003) x0, y0, z0
      write(*,5005) nposit
      y0 = y0*snell
      call submove(x0,y0,z0)
      y0 = y0/snell
c     write position header to output file
      write(3,5001) nposit,x0,y0,z0
c     get the data at this point
      call get_data(vx,vz,phi,nbin)

c     write the data out
      do 1002 j=1,nbin
c     reverse the IFA sign convention to correspond to SNAME
        vx(j)=-1.*vx(j)
        vz(j)=-1.*vz(j)
      write(3,5003) phi(j), vx(j),vz(j)
1002  continue
      nposit=nposit+1
      go to 900

1003  continue
4999  format(' Alpha = 'i3,'  RPM = ',f7.2)
5000  format(' Alpha = ',I3,' deg ',F6.1,' rpm test on ',I2.2,'-',I2.2,
     *  '-',I4.4,' at ',I2.2,I2.2)
5001  format(' Posit ',I5,3x,F9.3,3x,F9.3,3x,F9.3)
5003  format(3F10.3)
5004  format(A8,2x,A4)
5005  format(' Moving LDV to position number ',I4)
6000  continue
      close(1)
      close(3)
      end
```

```
c       ***********************************************************
c       *                                                         *
c       *              PERTURB.FOR                                *
c       *                                                         *
c       *                by                                       *
c       *                                                         *
c       *              Tom Eccles                                 *
c       *                                                         *
c       *              February 1990                              *
c       *                                                         *
c       ***********************************************************

c       This program takes the measured velocities and roll angles
c       for each position and converts the velocities and locations
c       to a body fixed coordinate system. The velocities are given
c       as perturbations from the ambient free stream flow.
$DEBUG
        program perturb
c       Declarations
        character*80 header
        character*20 invel, outvel
        character*8 date
        character*4 time
        integer*2 alpha,qbin,q34bin
        dimension phi(70,180),u0(70,180),w0(70,180)
        dimension u(70,180),v(70,180),w(70,180)
        dimension x0(70),y0(70),z0(70)
        dimension x(70,180),y(70,180),z(70,180)

        pi = acos(-1.)
c       Find input and output file names
        write(*,'(a)')' '
        write(*,'(a\)')' Type the INPUT velocity data filename ==>'
        read(*,'(a)') invel
        open(unit=1,file=i  vel,status='old')

        write(*,'(a)')' '
        write(*,'(a\)')' Type the OUTPUT velocity data filename ==>'
        read(*,'(a)') outvel
        open(unit=3,file=outvel)
1000    continue
        read(1,5001) alpha, rpm, date, time

        write(3,5006) alpha, rpm, date, time
        write(3,5002)
        nbin=180
c       Read sample points from input data file
        npts=0
1100    continue
        npts=npts+1
        read(1,5003,end=1201) nposit,x0(npts),y0(npts),z0(npts)
        do 1200 j=1,nbin
          read(1,5004) phi(npts,j),u0(npts,j),w0(npts,j)
c       Loop back to a new data point and begin again.
1200    continue
        goto 1100
1201    continue
        npts=npts-1
c       Find all the positions in body space (x,y,z)
        do 1250 k=1,npts
          do 1225 m=1,nbin
            x(k,m)=x0(k)*cos(alpha*pi/180)+sin(alpha*pi/180)*
     *  (y0(k)*sin(phi(k,m)*pi/180)-z0(k)*cos(phi(k,m)*pi/180))

            y(k,m)=y0(k)*cos(phi(k,m)*pi/180)+z0(k)*sin(phi(k,m)*
     *    pi/180)

            z(k,m)=x0(k)*sin(alpha*pi/180)-cos(alpha*pi/180)*
     *  (y0(k)*sin(phi(k,m)*pi/180)-z0(k)*cos(phi(k,m)*pi/180))
1225      continue
```

```
1250   continue

       hpts=npts/2
       qbin=nbin/4
       q34bin=3*nbin/4

       do 1350 k=1,hpts
         do 1325 m=1,qbin

            u(k,m)=-1*sin(alpha*pi/180)*
     *  (w0(k,m)*cos(phi(k,m)*pi/180)+
     *  w0(k+hpts,m+q34bin)*sin(phi(k,m)*pi/180))

            v(k,m)=w0(k,m)*sin(phi(k,m)*pi/180)-
     *  w0(k+hpts,m+q34bin)*cos(phi(k,m)*pi/180)

            w(k,m)=cos(alpha*pi/180)*
     *  (w0(k,m)*cos(phi(k,m)*pi/180)+
     *  w0(k+hpts,m+q34bin)*sin(phi(k,m)*pi/180))

1325     continue

         do 1335 m=qbin+1,nbin

            u(k,m)=-1*sin(alpha*pi/180)*
     *  (w0(k,m)*cos(phi(k,m)*pi/180)+
     *  w0(k+hpts,m-qbin)*sin(phi(k,m)*pi/180))

            v(k,m)=w0(k,m)*sin(phi(k,m)*pi/180)-
     *  w0(k+hpts,m-qbin)*cos(phi(k,m)*pi/180)

            w(k,m)=cos(alpha*pi/180)*
     *  (w0(k,m)*cos(phi(k,m)*pi/180)+
     *  w0(k+hpts,m-qbin)*sin(phi(k,m)*pi/180))

1335     continue

1350   continue

       do 1450 i=1,hpts

         do 1400 j=1,nbin
           write(3,5005) x(i,j),y(i,j),z(i,j),u(i,j),v(i,j),w(i,j)
1400     continue

1450   continue

1500   continue

5000   format(A8,2x,A4)
5001   format(9x,I3,5x,F6.1,13x,A10,4x,A4)
5002   format(8x,'X',11x,'Y',11x,'Z',11x,'U',11x,'V',11x,'W')
5003   format(7x,I5,3x,F9.3,3x,F9.3,3x,F9.3)
5004   format(3F10.3)
5005   format(6F12.3)
5006   format('Coning Angle = ',I3,' at ',F5.1,' rpm on ',A10,' at ',A4)

       close(unit=1)
       close(unit=3)

6000   continue


       end
```

```
      program vectors

c     This program will generate the PostScript file to produce
c     perturbation vectors in the body-fixed section on a laser printer


      integer alpha,num,nspace,hdata,rpm,q34data
      real x0
      character*20 indata, outps

      pi=acos(-1.)
      write(*,'(a)') ' Enter the INPUT data file name ==>'
      read(*,'(a)') indata
      open(3,file=indata,status='old')

      write(*,'(a)') ' '
      write(*,'(a)') ' Enter the output PostScript file name ==>'
      read(*,'(a)') outps
      open(5,file=outps,status='new')

      write(*,'(a)') ' '
      write(*,'(a)') ' Enter the number of lines of data ==>'
      read(*,*) ndata

      write(*,'(a)') ' '
      write(*,'(a)') ' Enter the coning angle ==>'
      read(*,*) alpha

      write(*,'(a)') ' '
      write(*,'(a)') ' Enter the rotation rate in rpm ==>'
      read(*,*) rpm

      write(*,'(a)') ' '
      write(*,'(a)') ' Enter Xo ==>'
      read(*,*) x0

      write(*,'(a)') ' '
      write(*,'(a)') ' Enter scale factor ==>'
      read(*,*) sfac

c     This establishes the requires PostScript header material

      write(5,'(a)')'%!PS-Adobe-1.0'
      write(5,'(a)')'%%BoundingBox: 0 0 612 792'
      write(5,'(9a,20a)')'%%Title: ',outps
      write(5,'(a)')'%%Pages: 1'
      write(5,'(a)')'%%DocumentFonts: Helvetica'
      write(5,'(a)')'%%EndComments'

      write(5,'(a)')'/m {moveto} def'
      write(5,'(a)')'/l {lineto} def'
      write(5,'(a)')'/s {stroke} def'
      write(5,'(a)')'/f {fill} def'
      write(5,'(a)')'/n {newpath} def'
      write(5,'(a)')'/arrow {newpath'
      write(5,'(a)')'     0 0 moveto'
      write(5,'(a)')'     1 0 lineto'
      write(5,'(a)')'     1 0 moveto'
      write(5,'(a)')'     0.75 0.10 lineto'
      write(5,'(a)')'     1 0 moveto'
      write(5,'(a)')'     0.75 -0.10 lineto} def'

      write(5,'(a)')'0.072 setlinewidth'
      write(5,'(a)')'2 setlinejoin'
      write(5,'(a)')'/Helvetica findfont'
      write(5,'(a)')'9 scalefont setfont'
      write(5,'(a)')'%%EndProlog'
      write(5,'(a)')'%%Page: 1 1'
      write(5,'(a)')'306 396 translate'
      write(5,'(a)')'1.1339 -1.1339 scale'
      write(5 '(a)')'gsave'


      shift=-1*x0*sin(alpha*pi/180.)
      write(5,'(2F6.3,a6)') sfac,sfac,' scale'
      write(5,'(a3,F7.3,a10)') '0 ',shift,' translate'
      write(5,'(a)')'gsave'

c     This reads thru the velocity data files and
c       produces the individual vectors

      read(3,'(a)') header
      read(3,'(a)') header
```

```
      hdata=ndata/2
      q34data=3*ndata/2

      do 100 j=1,ndata
        read(3,5000) x,y,z,u,v,w
        veclen=(sqrt(v**2+w**2))
        if ((v.eq.0.).and.(w.eq.0.)) then
          vecang=0.
          veclen=0.
        elseif ((v.eq.0.).and.(w.gt.0.)) then
          vecang=90.
        elseif ((v.eq.0.).and.(w.lt.0.)) then
          vecang=-90.
        elseif ((v.gt.0.).and.(w.eq.0.)) then
          vecang=0.
        elseif ((v.lt.0.).and.(w.eq.0.)) then
          vecang=180.
        elseif ((v.gt.0.).and.(w.ne.0.)) then
          vecang=(atan(w/v))*180./pi
        elseif ((v.lt.0.).and.(w.ne.0.)) then
          vecang=180.+(atan(w/v))*180./pi
        endif

        if (veclen.ne.0) then
          width=0.1/veclen
        else
          width=0.1
        endif

        if ((j.lt.hdata).or.((j.lt.q34data).and.(mod(j,3).eq.0))
     *  .or.(mod(j,6).eq.0)) then
        write(5,'(a)')'n'
        write(5,'(F9.3,a13)') width,' setlinewidth'
        write(5,'(2F9.3,a10)') y,z,' translate'
        write(5,'(F9.3,a7)') vecang,' rotate'
        write(5,'(2F9.3,a6)') veclen, veclen,' scale'
        write(5,'(a)')'arrow s'
        write(5,'(a)')'grestore'
        write(5,'(a)')'gsave'
        endif
100   continue
c     This draws the hull cross-section

      write(5,'(a)') 'n'
      write(5,'(a)')'0 0 34.2265 0 360 arc s'

c     This establishes the coordinate axes

      write(5,'(a)')'grestore'
      write(5,'(a)')'grestore'
      write(5,'(a)')'n'
      write(5,'(a)')'0.72 setlinewidth'
      write(5,'(a)')'/Helvetica findfont 9 scalefont setfont'
      write(5,'(a)')'n'
      write(5,'(a)')'-203.2 -203.2 m'
      write(5,'(a)')'-203.2 203.2 l'
      write(5,'(a)')'203.2 203.2 l s'

c     This draws the tic marks and labels them

      write(5,'(a)')'1 -1 scale'

      do 250 k=1,2
        fixed=-210.
        tic=-203.2

        do 200 m=1,21
          if (k.eq.1) then
            chars=-235.
            space=(11-m)*20
       num=-1*space/sfac-shift
            write(5,'(a)')'n'
            write(5,5002) fixed,space,' m'
       write(5,5003) tic,space,' l s'
       write(5,'(a)') 'n'
       write(5,5004) chars,space,' m (',num,') show'
          elseif (k.eq.2) then
            chars=-220.
            space=(m-11)*20
       nspace=space/sfac
       write(5,'(a)') 'n'
            write(5,5002) space,fixed,' m'
       write(5,5003) space,tic,' l s'
```

```
            write(5,'(a)') 'n'
            space=space-10.
            write(5,5004) space,chars,' m (',nspace,') show'
               endif
200          continue
250         continue
c           This labels the axes
            write(5,'(a)') 'n'
            write(5,'(a)')'/Helvetica findfont 12 scalefont setfont'
            write(5,'(a)')'-20 -240 m'
            write(5,'(a)')'(Y \(in mm\)) show'
            write(5,'(a)') 'n'
            write(5,'(a)')'/Helvetica findfont 16 scalefont setfont'
            write(5,'(a)')'-70 260 m'
            write(5,'(a)')'(Cross Flow Velocities) show'
            write(5,'(a)') 'n'
            write(5,'(a)')'/Helvetica findfont 10 scalefont setfont'
            write(5,'(a)')'-115. 245. m'
            write(5,5005)'(Coning Angle = ',alpha,' degrees, ',rpm,
     *      ' rpm, at Xo = ',x0,') show'
            write(5,'(a)') 'n'
            write(5,'(a)')'/Helvetica findfont 12 scalefont setfont'
            write(5,'(a)')'-240 0 m'
            write(5,'(a)')'90 rotate'
            write(5,'(a)')'(Z \(in mm\)) show'
            write(5,'(a)')'grestore'
            write(5,'(a)')'showpage'
            write(5,'(a)')'%%Trailer'
            write(5,'(a)')'%%EOF'
1000        continue
5000        format(6F12.3)
5002        format(2F7.0,A2)
5003        format(2F7.0,A6)
5004        format(2F7.0,A4,I4,A8)
5005        format(A16,I3,A10,I4,A14,F6.1,A6)
            close(3)
            close(5)
            end
```

```
$DEBUG
      program DC
c ------------------------------PROGRAM DC.FOR---------------------
c
c ----- Version:  1.3
c
c ----- Date:    August 1989
c
c ----- Purpose:  Main driver program that links with the following
c          programs:  Davlab, Common, DCDave and Calibr.For.
c          This program is to obtain readings from the balance,
c          store them (ac and dc), and convert the steady state
c          components to forces and moments.
c          Program for ROTATING measurements, DC forces
c          and moments.
c
c ----- Programmers:  Tom Eccles, Dave Johnson and Glenn Mckee
c
c ----- Language:  Microsoft Fortran 4.1
c
c ----- Variables:
c          fdata(i):  Raw MIT counts array filled with counts
c            from all a/d channels.  ("full" data)
c
c          pdata(i):  Raw MIT counts array with 6 preferred
c            channels of a/d channels.  Array values
c            are later corrected for zeros and convair
c            /MIT counts.  This array is then mult.
c            by a(i,j) for the balance loads.
c            ("preferred" data)
c
c          loads(i):  Array with balance loads.  loads(i) comes
c             from the matrix multiplication of pdata(i)
c            and a(i,j).
c
c          zerot(i):  Row array with averaged counts for all
c            a/d channels.  This array is read by the
c            subroutine "filter" to convert to the
c            preferred 6 channels and put into zeros(i).
c
c          a(i,j):  Coefficient matrix [B] .  From {L} = [B]{R}
c
c ----- Files:
c        rname:  Raw MIT counts file with data from all
c        a/d channels
c
c        Ratio: file of Convair R-cal/MIT R-cal readings for the
c             6 preferred channels.
c
c        M2X1T.DAT:  Balance coefficients for Roll bridge 2 and
c          Axial bridge 1, referenced to C of Rot.
c
c        *** Data Conventions Used in This Code ***
c
c          IndexReadings()Loads()
c            1Normal Force 1Normal Force at center
c            2Normal Force 2Pitch Moment at center
c            3Side Force 1Side Force at center
c            4Side Force 2Yaw Moment at center
c            5Selected Roll BridgeRoll Moment at center
c            6Selected Axial BridgeAxial Force at center
c
c        ( The zeros() and ratios() vectors use the same conventions as
c          the pdata() )
c
c ----------------------------------------------------------------------

      real pdata(6), loads(6), zeros(6), ratios(6), fdata(9)
      real zerot(9), dpc, rpmc, dp, rpma,iloads(6)
      character*3 tcase, zcase
      character*11 zname, lname, rname,iname,calibr
      character*80 id, header,head1,headc
      character ans

      common /dpcell/ rho, zero, full, tt
      common /rpm/ rvz, rvcal
      common /revsect/ nrev,nsect
```

```
c ----- open files
        open (unit=10, file = 'ratio' , status = 'old' )

        write (*,*)
        write (*,*) '          *** PROGRAM DC.FOR *** '
        write (*,*)

cdb --- Debug commands for reading in Convair test case.  This is to
cdb     check the data reduction algorithm .....
cdb     goto 52

        write (*,*) ' Note:  Zeros for this program are stored in the'
        write (*,*) '       file aawww.CTS.  The program zero should be'
        write (*,*) '       run first to get the proper DAILY zeros. '
        write (*,*)
        write (*, '(A\)') ' Input the zero (cts) filename (I/HFaa.CTS): '
        read (*,1) zname
        write (*,*)

c ----- Read in zeros from file zname
        open (unit = 2, file = zname , status = 'old')
        read (2,' (a80)') header
        read (2,' (a80)') id
        read (unit =2, fmt = 2, err = 51) zcase, (zerot(i) , i = 1,9)
        write (*,*)
        write (*,*) ' Zeroes read in successfully! '
        write (*,*)
c -----Debug command
        write (*,*) zerot(1),zerot(9)
        goto 52
51      write (*,*)
        write (*,*) ' Error in reading zero file '
        goto 100
52      continue

c ----- Read in ratios from file of preferred channels (file "RATIO")
        read (unit = 10, fmt = 6, err = 55) (ratios(i) , i=1,6)
        write (*,*)
        write (*,*) ' Ratios read in successfully'
c -----Debug command
        write (*,*) ratios(1),ratios(6)
        goto 56
55      write (*,*) ' Error in reading in ratios'
        goto 100
56      continue

cdb --- Debug for reading in Convair test case ....
cdb     goto 57

c ----- Call filter subroutine for producing zeros(i)
        call filtz (zerot,zeros)

57      continue

c       ... assign a vacant FORTRAN unit number ...
        lunit = 3
c       ... use the CONVAIR preferred set of coefficients (R2X1) ...
        item = 4
        call intcoef( lunit, item  )
        Write (*,*) ' Coefficient Data has been read '

c       ... these are the A/D readings without applied external forces ...
        call setzero( zeros )

c       ... these are the ratios of the current signals divided by the ...
c       ... original signal levels at calibration ...
        call setrcal( ratios )

cdb --- Debug for reading in Convair test case .....
cdb     goto 58

c ----  Offer option of either taking data or processing a previous
c       run's data .....
70      write (*,*)
        write (*,*) ' Do you wish to take new data or process'
        write (*,' (a\)') ' old data ? (N/O): '
        read (*, fmt=9) ans
        if ((ans .eq. 'N').or.(ans .eq. 'n')) then
```

```
c ----- Calibrate or read from an old calibration file?
            write (*,*)
            write (*,' (a\)') ' Calibrate? (y/n):'
            read (*,9) ans
            if ((ans .eq. 'n').or.(ans .eq. 'N')) then
          write (*,*)
          write (*,' (a\)') ' Input old cal file (date.CAL): '
          read (*,1) calibr
          open(unit=5, file=calibr,status='old')
          read (5,' (a80)') headc
          read (5,' (a80)') id
          read (5,15) rho,zero,full,tt,rvz,rvcal
          close (unit=5)
          goto 80
            endif

c ----- Call calibration routines .....
            call dpcal
            call rpmcal

c ----- write result of recent calibration to file Calibr....
            write (*,*)
            write (*,' (a\)') ' Input new calibration file (date.CAL): '
            read (*,1) calibr
            write(*,*) ' Type in new calibration file header: '
            read (*,' (a80)') headc
            open (unit=5,file=calibr)
            write (5,' (a80)') headc
            write (5,17)
            write (5,15) rho,zero, full,tt,rvz,rvcal
            close(unit=5)

80          write (*,*)
c -----     write (*,' (a\)') ' Input # of revolutions, nrev: '
c -----     read (*,3) nrev
c -----     write (*,*)
            write (*,' (a\)') ' Type in tcase (3 max): '
            read (*,' (a3)') tcase
            nsect = 32
            nrev = 10

c --------- Go to data taking subroutine
            Call takedata (fdata,dpc,rpmc,tcase,header)
            write (*,*) ' takedata finished! '
            write (*,*)

c --------- debug command
cdb         pause
            goto 62
          endif

cdb --- Debug for reading in Convair test case or for inputing
c         previous run file ....
58        continue
          write (*,*)
          write (*,'(A\)')' Input OLD net counts file (I or Hdaawww.NET): '
          read (*,1) rname
          write (*,*)
          open (unit=9, file = rname, status = 'old')
          read(9,' (a80)') header
          read(9,' (a80)') id
          read (unit=9,fmt=18,err=61) tcase,(fdata(i), i=1,9),dpc,rpmc
          write (*,*) ' Previous counts .....'
          write (*,*) fdata(1), rpmc

c ----- Read in old calibration file.....
          write (*,*)
          write (*,' (a\)') ' Input old calibration file (date.CAL): '
          read (*,1) calibr
          open(unit=5, file=calibr,status='old')
          read (5,' (a80)') header
          read (5,' (a80)') id
          read (5,15) rho,zero,full,tt,rvz,rvcal
          close (unit=5)

cdb       do 60 j = 1,6
cdb         zeros(j)=0.0
cdb60     continue
          goto 62

61        write (*,*) ' Error in reading Previous counts....'
          goto 100
62        continue
```

```
c ********************* Data Reduction Portion *************************

c ----- Call filter subroutine to reduce the readings to the preferred
c       6 channels (i.e. read in data to pdata(i))
        call filter(fdata, pdata)

        write (*,*) ' filter done '
c ----- debug command
cdb     pause

        write (*,*)
        write (*,*) '   Now Processing Data!!! '
        write (*,*)

c       ... adjust the values by removing the zeros and compensating ....
c       ... for the ratio of the signal level ...
        call doadjus( pdata )

        call doload( pdata, loads, ierr )
        if( ierr .ne. 0 ) then
          write(6,12) tcase
        endif
  20    continue

c ----- Convert dpc and rpmc counts to velocity and rpm...
        call rpmvel(dpc,rpmc,dp,rpma)

c ----  Write loads to screen
        write (*,*)
        write (*,*) '  Loads for this run... '
        write (*,*)
        write (*,10)
        write (*,7)  tcase, (loads(i) , i=1,6),dp,rpma

c ---- Ask if INERTIA run or HYDRO run.  This determines whether or not
c    the inertial forces are subtracted out from the above loads.....
75      write (*,*)
        write (*,' (a\)') ' Is this an inertial or hydro run? (i/h):'
        read (*,9) ans
        if ((ans .eq. 'h').or.(ans .eq. 'H')) then
          write (*,*)
          write (*,'(a\)')' Input Inertial LOADS file (Idaawww.LOD): '
          read (*,' (a11)') iname
          open (unit=6, err=75,file=iname,status='old')
          read(6,' (a80)') head1
          read(6,' (a80)') id
          read (6,16) tcase,(iloads(i), i=1,6)
          close(unit=6)

c --------- Do Load subtraction .....
          do 85 i=1,6
        loads(i)=loads(i)-iloads(i)
85        continue
        endif

c ----- Write loads to file lname.....
        write (*,'(A\)')' Input load output filename (I or Hdaawww.LOD): '
        read (*,1) lname
        write (*,*)

        open(unit=7, file = lname, status = 'new' )
c -----  write (*,*) ' Input header for load file . . . . '
c -----  read (*,' (a80)') header
        write (7,' (a80)') header
        write (7,10)
        write(7,7) tcase, (loads(i), i=1,6),dp,rpma

c ---- Write loads to screen again.....
        write (*,*)
        write (*,*) '  Final loads for this run... '
        write (*,*)
        write (*,10)
        write (*,7)  tcase, (loads(i) , i=1,6),dp,rpma

        write (*,*)
90      write (*, ' (A\) ' ) ' Would you like another test run? (y/n) : '
        read (*,fmt =9, err = 90) ans
        m=m+1
        if ((ans .EQ. 'y').or.(ans.eq.'Y')) goto 70
```

```
c ----- Format Statements .....
1       format(A11)
2       format (A3, 9F7.1)
3       format (i2)
6       format (6F8.4)
7       format (A3, 6F9.4,2f9.2)
9       format (A1)
10      format('TC',4X,'Z',8X,'M',8X,'Y',8X,'N',8X,'K',
     +        8X,'X',8x,'VEL',6x,'RPM')
12      format(' Convergence problem on point ',A10)
15      format (6f9.5)
16      format(a3,6f9.4)
17      format (3x,'Rho',6x,'Zero',5x,'Full',6x,'Tt',6x,'Rvz',
     +  6x,'Rvcal')
18      format (a3,11F7.1)
c ----- Close all remaining open files .....
        close(unit = 10)
        close(unit = 7)
        close(unit = 1)
        close(unit = 2)

100     continue
        end



$DEBUG
c ---------- PROGRAM DCDAVE.FOR ----------
c
c ----- Version:  1.3
c
c ----- Note:  Full Revolution Version , Therefore nrev=10  max!
c
c ----- Date:  29 March 1989
c
c ----- Purpose :  To provide the collection of subroutines necessary
c           for rotating data taking and DC processing.This
c           program is for linking with the main driver program
c           DC.FOR.
c
c ----- Programmer:  Tom Eccles and Dave Johnson
c
c ----- Language:  Microsoft Fortran 4.1
c
c ----- Subroutines:
c         TAKEDATA:  Primary rotary data collection sub-
c           routine
c
c         FILTER:  Reduces readings to the preferred 6
c          channels for later processing
c
c         FILTZ:Reduces zero readings to 6 preferred
c         chanels for later processing
c
c         RPMVEL:  Converts dp and rpm counts to actual
c          tunnel velocity and model rpm
c ***************************************************************************
        SUBROUTINE TAKEDATA(fdata,dpc,rpmc,tcase,header)
c ---------- SUBROUTINE TAKEDATA----------
c
c ----- Arrays:    fdata(i,j):  Averaged (over nsamp) raw MIT counts
c          for all 9 a/d channels of balance data.
c
c            iarray(i):Row array filled by EACH mcbatod call
c
c            tarray(i,j):  Temporary array with rows of iarray
c           and columns of nrev*nsect samples
c
c            bigarray(i,j): Summed counts array that is divided
c           by nsamp and written to tares(i,j)
c
c            dpc(i):  Raw MIT counts read from dpcell
c
c            rpmc(i):  Raw MIT counts read from daytronix chan C
c
```

```
c ----- Files:   RCxxxx.xxx:  Raw data file in MIT counts.
c
c ---------------------------------------------------------------------

c ----- Dimensions set for max of 32 sectors/rev x 10 revs = 96 data pts
c       and max of 11 channels sampled at 3 samples/channel .....
        integer*2 iarray(33), tarray(320,33), nval, n, m, nsamp
        integer*2 nchan, echan, k
        real rfdata(320,9), bigarray(320,11), frpmc(320), fdpc(320)
        real rpmc,dpc,rpma,dp,sum1(32,11),fdata(9)
        character*11 rname,rsum,tsum
        character*80 header
        character*3 tcase

        common /revsect/ nrev, nsect

        nchan = 11
        echan = 10

c ----- Setclock set for 1kHz
        call mbopen
        call setclock(.001,0)

c ----- Input data counts filename and # of samples to be taken at
c       each data point .....
        write (*,*)
        write (*,*) ' Format for Raw Counts File is Idaawww.RAW '
        write (*,*) ' or Hdaawww.RAW where d is either F or R for '
        write (*,*) ' rotation direction, aa is coning angle, '
        write (*,*) ' and www is rotation rate in rpm.'
        write (*,*)
        write (*,'(A\)')' Input Raw Output Filename (I/Hdaawww.RAW): '
        read (*, 5) rname
        open (unit = 1, file = rname)

        write (*,*)
c -----  write (*,*) ' Before entering # of samples per data point, '
c -----  write (*,*) ' remember that for any high speed data taking, '
c -----  write (*,*) ' nsamp should not be > 1. '
c -----  write (*,*)
c -----  write (*, ' (A\) ') ' Input # of samples for each data point: '
c -----  read (*, 6) nsamp
        nsamp = 1

        write (*,*)
        pause 'Press any key to start data taking ..... '

c ----- The following logic is based on inputs to the digital input
c       ports #0 and #1 being 32(J) and 1/rev(K) pulses respectively.
c       The elaborate if-then statements ensure that the data taking
c       actually starts at 0 degrees and counts for nrev revolutions.

c ----- Initialize counters .....
        n = 0
        m = 0
        k = 0
        call dina(nval)

c ----- If the following expression is true, then K is low....
100     if (nval .le. 1) goto 200
        call dina(nval)
        goto 100

c ----- If the following expression is true, then K is high and thus
c       the model is at 0 degrees.  Now start counting 32 times for 1
c       revolution and then start taking data on 33rd count.....
200     call dina(nval)
250     if (nval .ge. 2) goto 290
        call dina(nval)
        goto 250

c ----- Start counting 32 times off J trigger
290     call dina(nval)
300     if ((mod(nval,2)) .EQ. 1) goto 400
        call dina(nval)
        goto 300
400     n = n + 1
        if (n .EQ. 32) goto 500

c ----- Look for J low .....
450     if ((mod(nval,2)) .EQ. 0) goto 290
        call dina(nval)
        goto 450
```

```
c ----- Look for J low before taking data ....
500     if ((mod(nval,2)) .EQ. 0) goto 600
        call dina(nval)
        goto 500

c ----- Look for J high to trigger data taking.  This ensures start at
c       0 degrees....
600     call dina(nval)
650     if ((mod(nval,2)) .EQ. 1) goto 700
        call dina(nval)
        goto 650

c ----- Now at 0 degrees, begin taking data .....
700     call mcbatod (0,echan,1,nsamp, iarray)
        m = m+1

c ----- Throw temporary data into tarray to prevent overwrite of data ....
        do 750 i=1, (nsamp*nchan)
           tarray (m,i) = iarray (i)
750     continue

c ----- Exit condition: exit loop after nrev revs of data taking (10 max)
        if (m .EQ. (nrev*nsect)) goto 755

c ----- Look for J low, if J is low, go up to top of loop and look for
c       J high again.  This prevents multiple triggers off the same
c       pulse, especially important for slow rpm runs .....
751     if ((mod(nval,2)) .EQ. 0) goto 600
        call dina(nval)
        goto 751

c ----- Done taking data, now put into proper arrays and store in file....
        write (*,*)
        write (*,*) ' Done taking data .....'
        write (*,*)

c ----- Fill array bigarray(i,j) with zeroes ....
755     do 760 i= 1, (nrev*nsect)
           do 760 j = 1, (nchan)
        bigarray(i,j) = 0.0
760     continue

c ----- Place sum of nsamp number of data points in each storage bin ....
765     do 780 i = 1, (nrev*nsect)
           do 780 j = 1, (nchan)
        bigarray(i,j) = bigarray(i,j) + tarray(i, (j+(nchan*k)))
780     continue

        k = k+1
        if (k .EQ. nsamp) goto 781
        goto 765
781     continue

c ----- Next, divide the samples by nsamp and put in arrays rfdata(i,j),
c       fdpc(i) and frpmc(i)
        do 791 i = 1, (nrev*nsect)
           do 790 j = 1, 9
        rfdata(i,j) = bigarray(i,j)/nsamp
790        continue
        fdpc(i) = (bigarray(i,10))/nsamp
        frpmc(i) = (bigarray(i,11))/nsamp
791     continue

c ----- Finally, put data values into the data file rname .....
        write (*,*)
        write (*,*) ' Type in file Header .....'
        read (*,' (a80)') header
        write (1,' (a80)') header
        write (1,14)
        write (*,*) ' Processing Raw Data .....'
        do 795 i = 1, (nrev*nsect)
           write (1,15) (rfdata(i,j) , j = 1,9), fdpc(i), frpmc(i)
795     continue

c ---------- DATA HANDLING ----------

c ----- Sum up nrev points into 1 rev of data and put into file ...
c       Fill sum1, fdata, dpc, and rpmc with zeros ....
        do 82 i = 1, 11
        do 82 j = 1, nsect
        sum1(j,i) = 0.0
82      continue
```

```
      do 81 i = 1,9
        fdata(i)=0.0
81    continue
      dpc = 0.0
      rpmc = 0.0

c ----- First do balance counts ....
      k = 0
83    do 85 i = 1, 9
      do  85 j = 1, nsect
      sum1(j,i) = sum1(j,i) + rfdata(j+(nsect*k),i)
85    continue
      k = k + 1
      if (k .eq. nrev) goto 86
      goto 83
86    continue

c ----- Now do dp and rpm measurements .....
      k = 0

89    continue
      do 90 j = 1,nsect
      sum1(j,10) = sum1(j,10) +fdpc(j+(nsect*k))
      sum1(j,11) = sum1(j,11) + frpmc(j+(nsect*k))
90    continue
      k = k + 1
      if (k .eq. nrev) goto 91
      go to 89

c ----- Divide by nrev for averaged values over 1 revolution ...
91    do 110 i=1, 11
      do 110 j = 1, nsect
      sum1(j,i) = sum1(j,i)/nrev
110   continue

c ----- Now sum up over remaining revolution for averaged counts .....
      do 95 i = 1, 9
      do 95 j = 1, nsect
      fdata(i) = fdata(i) +sum1(j,i)
95    continue

c ----- Again, do dp and rpm ....
      do 105 j = 1 , nsect
      dpc = dpc + sum1(j,10)
      rpmc = rpmc + sum1(j,11)
105   continue

c ----- Divide by nsect ......
      do 120 i=1,9
      fdata(i) = fdata(i)/nsect
120   continue

      dpc = dpc/nsect
      rpmc=rpmc/nsect

c ----- Write sum1 and fdata, dpc, rpmc, to files ...
      write (*,*)
      write (*,'(A\)') ' Input SUMMED (1 rev) file (I/Hdaawww.SUM): '
      read(*,1) rsum
      write (*,*)
      write (*,' (A\)') ' Input NET output file (I/Hdaawww.NET): '
      read (*,1) tsum
      open (unit = 15, file = rsum, status = 'new')
      open (unit = 16, file = tsum, status = 'new')
      write (15,' (a80)') header
      write (16,' (a80)') header
      write (15,14)
      write (16,10)
      write (16,7) tcase,(fdata(i), i = 1,9),dpc,rpmc
      do 130 j = 1,nsect
      write(15,15) (sum1(j,i), i = 1,11)
130   continue

c ----- FORMAT statements .....
1     format (a11)
5     format (a11)
6     format (I2)
7     format (a3,11f7.1)
10    format('TC',4x,'N1',5x,'N2',5x,'Y1',5x,'Y2',5x,'R1',
     +  5x,'R2',5x,'X1',5x,'X2',5x,'X3',5x,'DP',4x,'RPM')
14    format(3x,'N1',5x,'N2',5x,'Y1',5x,'Y2',5x,'R1',
     +  5x,'R2',5x,'X1',5x,'X2',5x,'X3',5x,'DP',5x,'RPM')
15    format (11F7.1)
```

```
1000    continue
        close (unit = 1)
        return
        end
c ***************************************************************
        subroutine filtz(zerot,zeros)
c ---------------------- SUBROUTINE FILTZ ---------------------
        real zerot(9), zeros(6)
        do 30 i= 1,4
          zeros(i) = zerot(i)
30      continue
        zeros(5) = zerot(6)
        zeros(6) = zerot(7)
        return
        end
c ***************************************************************
        subroutine filter(fdata, pdata)
c --------------- SUBROUTINE FILTER ------------------------------
c
c ----- Date: 16 Feb 1989
c
c ----- Purpose:  Filter subroutine to take all channels of data and read
c           in the 6 preferred channels for processing by Maintst.
c
c ----- Variables :
c
c             fdata(i):  array with all channels of data (11)
c             pdata(i):  array with 6 preferred channels of
c            balance data.
c
c ------------------------------------------------------------------
        real pdata(6),fdata(9)
c ----- debug command
cdb     write (*,*) ' Have reached subroutine filter '
cdb     pause
c ----- Do test reading conversion
        do 10 i=1,4
        pdata(i) = fdata(i)
10      continue
c ----- debug command
cdb     write (*,*) ' First 4 points read in successfully '
        pdata(5) = fdata(6)
        pdata(6)= fdata(7)
        return
        end
c ***************************************************************************
        subroutine rpmvel (dpc, rpmc, dp, rpma)
c ---------------------------SUBROUTINE RPMVEL ---------------------
c
c ----- Purpose:  To convert dpcell and rpm readings to actual
c           velocities and rpm's.
c
c ------------------------------------------------------------------
        real dpc, rpmc, dp, rpma
        common /dpcell/ rho,zero,full,tt
        common /rpm/ rvz,rvcal
c ----- Convert dp counts to voltages and convert to ft/sec
c       using 409.6 counts/volt and Lisa's function dpspeed .... ..
          dpc = (dpc)/409.6
          dp = dpspeed(dpc)
c ----- Convert rpm counts to rpm's
          rpmc = (rpmc)/409.6
          rpma = (revs(rpmc))*60/512
        return
        end
```

```
c ----------Program DAVLAB.FOR----------

      subroutine doload( pdata, loads, ierr )

c ----------Subroutine doload----------

      real pdata(6), loads(6)
      integer ierr

c     *** The subroutine takes the readings corrected for zeros and ***
c       and scaling, and then converts them to equivalent loads
c       using a linear 6th order fit determined by the Davidson
c       Laboratory MCB program.
c     ************************************************************************

      common /convair/ a(6,6)

c     ... there is no possible error in this case ...
      ierr = 0

c     ... do the matrix multiplication ...
      do 20 i = 1, 6
        loads(i) = 0.0
        do 10 j = 1, 6
      loads(i) = loads(i) + a(j,i)*pdata(j)
   10 continue
   20   continue

c     ... done, so return ...
      return
      end

C ----------  ----------Subroutine intcoef----------

      subroutine intcoef( runit, item )
      integer runit, item

c     *** Subroutine to obtain the necessary information from a file ***
c       and to store it for later use of the conversion routines.
c
c         RUNIT:An available FORTRAN unit number for reading the
c     data file
c
c         ITEM:The set of coefficients selected for use in the
c     conversion routine.
c     ITEM #Selection
c     Roll Bridge   Axial Bridge
c      1   1          1
c      2   1          2
c      3   1   3
c      4   2          1
c      5   2          2
c           6            2   3
c     ************************************************************************

      character*80 id
      character*9 name(6)
      common /convair/ a(6,6)

      data name/ 'M1X1T.DAT', 'M1X2T.DAT', 'M1X3T.DAT',
     1   'M2X1T.DAT', 'M2X2T.DAT', 'M2X3T.DAT'/

c     *** attempt to open the data file ***
      open( unit=runit, file = name(item), status = 'old', err= 70 )

c     *** insure that zero is the default value ***
      do 10 i = 1, 6
        do 10 j= 1, 6
          a(i,j) = 0.0
   10   continue

c     *** read the contents of the file ***
      read(runit,15) id
   15 format(a80)
      do 20 i = 1, 6
        read(runit,*,end=25,err=25) ( a(i,j), j=1, 6 )
   20   continue
      goto 30
   25 print *,'    ERROR - Trouble reading Coefficient Data'
      return
   30 continue
cdb   write(6,40) id
```

```
c ---  debug commands
c        open (unit = 6, file = 'loadcoef', status = 'new' )
c  40  format(1x,a80)
c        do 60 i = 1, 6
c           write(6,50) i, (a(i,j), j=1,6)
c  50       format(1x,i4,6f12.6)
c  60       continue
c ----   debug command
c        close (unit = 6)
         close( runit )
         return
   70    write(6,80) name(item)
   80    format(5x,'ERROR - Data file ',a9,' can not be read'/
    1          5x,'       All coefficients are zero'//)
         end


$DEBUG
c ------------------------Program CALIBR.FOR-----------------------------
c ----- This program contains the calibration subroutines for calibrating
c        the dpcell and rpm channel.
      SUBROUTINE DPCAL
c
c        Calibrates the differential pressure cell.
c        Stores the calibrations "zero", and "full"
c        in the common block called "dpcell".
c
c
c        After calling DPCAL once in your program,
c        a special function exists in the MHL library
c        that you can use to convert voltages from
c        the Daytronics channel C to velocity.  It
c        is called "dpspeed", and has one calling
c        parameter, "voltage".
c
c
c        Example:
c
c        call dpcal
c          .
c          .
c          .
c        <do an A/D conversion on channel 2 (Daytronics C)>
c        freestream=dpspeed(voltage)
c          .
c          . etc
c
c        You do not have to include the common block in your
c        main program to make these routines work
c
c        Lisa Shields
c        June 12, 1987
         common /dpcell/ rho,zero,full, tt
         integer*2 channel,ig,ival
         character ans, line*70


         write(*,*)
         write(*,*) '              Welcome to Dpcal!'
10       write(*,*)
         write(*,'(A\)') '    Please input water temp (deg f): '
         read(*,*,err=10) tt
         rho=1.9574-0.00028*tt
100   FORMAT(5x,a70)
         write(*,*)
99       write(*,*)
         line='The dpcell should be connected to the Daytronic channel c'
         write(*,100) line
         write(*,*)
         line='The span and balance should be set such that the digital'
         write(*,100) line
         line='display reads from -820 (zero flow) to +600 (with '
         write(*,100) line
         line='the "-cal" button depressed.) '
```

```
        write(*,100) line
      write(*,*)
        write(*,*)
        write(*,*)
        write(*,101)
101     format(5x,'Please hit return after checking this ',\)
        read(*,104) ans
        write(*,*)
        line='Sampling zero flow voltage for 5 seconds and averaging'
        write(*,100) line

        call mbopen
        call setclock(0.01,0)
        zero=0.0
        channel=9
        ig=1
        do 110, i=1,500
        call atodtk(channel,ig,ival)
110     zero=zero + ival
        zero=zero/500.0/409.6

        write(*,*)
        line='Sampling finished.'
        write(*,100) line
        write(*,*)
        write(*,*)
        line='Now please press the "-cal" button and hold it down'
        write(*,100) line
        write(*,111)
111     format(5x,'for 5 seconds.  Hit return when ready',
     ^      ' to do this.',\)
      read(*,104) ans
        write(*,*)
        write(*,*)
        line='Sampling simulated full scale speed and averaging'
        write(*,100) line

        call setclock(0.01,0)
        full=0
        do 120 i=1,500
        call atodtk(channel,ig,ival)
120     full=full + ival
        full=full/500.0/409.6

        write(*,*)
        line='Sampling finished.'
        write(*,100) line
        write(*,*)
        write(*,*)
        write(*,102)zero, full
102   FORMAT(5x,'Zero voltage: ',F6.3,' Full scale voltage: ',F6.3)
        write(*,*)
        write(*,'(A\)') '    Accept these? (y/n): '
        read(*,104) ans
        if(.not.((ans .eq. 'y') .or. (ans .eq. 'Y'))) goto 99
        write(*,*)
      RETURN
104     format(a)
      END

c ---------------------Subroutine RPMCAL-------------------------

        Subroutine rpmcal
        common /rpm/ rvz, rvcal
        integer*2 channel
        character ans*1


c       This subroutine is used to calibrate the Daytronics
c       channel B, used to record propeller rpm data
        write(*,*)
        write(*,*)
5       write(*,10)
10      format(10x,'Welcome to the RPM (Channel B)',
     ^      ' calibration routine.')
15      write(*,*)
        write(*,*)
        write(*,20)
20      format(15x,'A:  Set Zero to read 000')
```

```
      write(*,30)
30    format(15x,'B:  Push cal button, adjust span to 1500')
      write(*,*)
      write(*,*)
      pause ' With propeller stopped, take time to do this now!'

      write(*,*)
      write(*,*)
      write(*,40)
40    format(1x,'Hit any key while holding down channel B',
     ^  ' cal button for 5 seconds:')
      read(*,41) ans
41    format(a)

      channel=10
      rvcal=average(.05,channel)

      write(*,*)
      write(*,*)
      write(*,50)
50    format(1x,' Please release cal button, and hit any',
     ^  ' key to take rpm zero: ')
      read(*,41) ans

      rvz=average(0.05,channel)

      write(*,*)
      write (*,55) rvz,rvcal
55    format (2x,'Rvz = ',f7.4,5x,'Rvcal = ',f7.4)
      write (*,*)
      write(*,' (a\)') ' Do you wish to recalibrate? (y/n): '
      read(*,41) ans
      if (ans .ne. 'n') goto 5
      return
      end




c ------------------------Program COMMON.FOR-----------------------------


c -------------------------Subroutine doadjus-----------------------------
      subroutine doadjus( pdata )
      real pdata(6)

c     *** This subroutine takes the current readings, corrects for the ***
c        readings for zero applied load, and then scales the result
c        back to the levels at which the calibration was done.  The
c        returned values should be the bits that would be read at
c        CONVAIR calibration bench.
c     ************************************************************************

      common /convar1/ zero(6), rcal(6)

      do 10 i = 1, 6
c        ... remove the zero first ...
         pdata(i) = pdata(i) - zero(i)
         pdata(i) = pdata(i)*rcal(i)
10       continue

      return
      end

c ---------------------------Subroutine setzero-----------------------
      subroutine setzero( zeros )
      real zeros(6)

c     *** This subroutine takes zero applied load readings and stores ***
c     *** them for later use ***

      common /convar1/ zero(6), rcal(6)

      do 10 i = 1, 6
         zero(i) = zeros(i)
10       continue

      return
      end

c ----------------------------Subroutine setrcal ----------------------
      subroutine setrcal( ratios )
      real ratios(6)
```

```
c       *** This subroutine takes calibration signal ratios and stores ***
c       *** them for later use ***
        common /convar1/ zero(6), rcal(6)

        do 10 i = 1, 6
          rcal(i) = ratios(i)
 10       continue

        return
        end


$DEBUG
c --------------------Program DAVEAST.FOR-------------------------------
        subroutine quickrd(fdata,tcase,m)
c --------------------Subroutine Quickrd--------------------------------
c
c ------Date: 19 Feb 89
c
c ------Pupose: To take static (w=0) measurements for combinations of
c               coning angles and roll angles. This subroutine is for
c         doing runs with the static TEST driver Mainast.for.
c
c ------Programmer:  Dave Johnson
c
c ------Language :  Microsoft Fortran 4.1
c
c ------Varibles:
c               iarray:  row array in DMA filled by each MCBATOD
c                        call.
c             fdata(i): array with averaged counts from all 11
c             channels.
c
c ----- Files:    Reading.tst:  Raw counts file of "averaged" counts
c                        from each of the 9 channels.
c
c ---------------------------------------------------------------------

        integer*2 iarray(2000),bchan,echan,nsamp,nchan,m
        real fdata(16)
        character*10 tcase
        character*11 rname
c
c ------Setclock set for 1kHz

        call mbopen
        call setclock(.001,1)

        write (*,*)
        write (*, ' (A\) ') ' Type in test case : '
        read (*, ' (A10) ' ) tcase

c ----  following allows the testor to skip this mundane data entry
c       for multiple runs.
        if (m .NE. 0) goto 40

cdb --  write (*,*)
cdb --  write (*,' (A\) ') ' Input Starting A/D Channel to Sample: '
cdb --  read (*,5) bchan
        bchan = 0
5       format (I2)

cdb --  write (*,*)
cdb --  write (*,' (A\) ') ' Input Ending A/D Channel to Sample: '
cdb --  read (*,5) echan
        echan = 8

        write (*,*)
        write (*,' (A\) ') ' Input Number of samples (e.g. 100): '
        read (*,6) nsamp
6       format (I4)

        write (*,*)
        write (*,'(A\)')' Type raw counts output file (HFaa00.RAW):'
        read (*,4) rname
4       format (A11)
        open (unit = 1, file = rname)

40      write (*,*)
        pause ' Press enter to start data taking '
c
c ------Take Static Data!!! ---------
```

```
          call MCBATOD (bchan,echan,1,nsamp,iarray)
c ----- calculate number of channels sampled
          nchan= (echan - bchan) + 1
          k=0
c ----- fill fdata(i) with zeros
          do 50 i=1,nchan
            fdata(i) = 0.0
50        continue
c ----- read in data to fdata(i)
55        do 60 i=1, nchan
            fdata(i) = fdata(i) + iarray(i+(nchan*k))
60        continue
          k=k + 1
          if (k .EQ. nsamp) goto 71
          goto 55
71        continue
c ----- Next, divide the values in fdata(i) to get averaged values
          do 80 i=1,nchan
            fdata(i) = (fdata(i))/nsamp
80        continue
c ----- Write fdata(i) to file "reading.tst"
          write(1,14)
          write(1,15) tcase, (fdata(i) , i=1,nchan)
7         format (A10,11F6.0)
14        format (3x,'N1',5x,'N2',5x,'Y1',5x,'Y2',5x,'R1',
     +    5x,'R2',5x,'X1',5x,'X2',5x,'X3')
15        format (A3, 9F7.1)
          write (*,*)
          write (*,*) ' Raw counts from Balance '
          write (*,14)
          write (*,15)  tcase, (fdata (i) , i = 1,nchan)
          write (*,*)
          return
          end
c ---------------------------------------------------------------------------
c ---------------------------------------------------------------------------
c
c ----------Subroutine filter----------------------------------------
c
c ----- Date: 16 Feb 1989
c
c ----- Purpose:  Filter subroutine to take all channels of data and read
c           in the 6 preferred channels for processing by Maintst.
c
c ----- Variables :
c
c              fdata(i):  array with all channels of data (11)
c              pdata(i):  array with 6 preferred channels of
c             balance data.
c
c ---------------------------------------------------------------------------
          subroutine filter(fdata, pdata)
          real pdata(6),fdata(16)
c ----- debug command
cdb       write (*,*) ' Have reached subroutine filter '
cdb       pause
c ----- Do test reading conversion
          do 10 i=1,4
          pdata(i) = fdata(i)
10        continue
c ----- debug command
cdb       write (*,*) ' First 4 points read in successfully '
          pdata(5) = fdata(6)
          pdata(6)= fdata(7)
c ----- Now do ratio conversion
c
c         do 20 i=1,4
c         ratios(i)=ratiot(i)
c 20      continue
c         ratios(5) = ratiot(6)
c         ratios(6) = ratiot(7)
```

```
        return
        end
c -------------------------Subroutine Filtz----------------------
        subroutine filtz(zerot,zeros)
        real zerot(16), zeros(6)

        do 30 i= 1,4
          zeros(i) = zerot(i)
30      continue
        zeros(5) = zerot(6)
        zeros(6) = zerot(7)

        return
        end


$DEBUG
        program mainast
c -------------------------------PROGRAM MAINAST.FOR--------------------
c
c ----- Date:  19 Feb 1988
c
c ----- Purpose:  Main driver program that links with the following
c           programs:  Davlab.For, Common.for, Daveast.for.
c           This program is to obtain CORRECTED readings
c           from the balance and convert them to forces and
c           moments.  Program for STATIC measurements!
c
c ----- Programmer:  Dave Johnson and Glenn Mckee
c
c ----- Language:  Microsoft Fortran 4.1
c
c ----- Variables:
c           fdata(i):  Raw MIT counts array filled with counts
c             from all a/d channels.  ("full" data)
c
c           pdata(i):  Raw MIT counts array with 6 preferred
c             channels of a/d channels.  Array values
c             are later corrected for zeros and convair
c             /MIT counts.  This array is then mult.
c             by a(i,j) for the balance loads.
c             ("preferred" data)
c
c           loads(i):  Array with balance loads.  loads(i) comes
c              from the matrix multiplication of pdata(i)
c             and a(i,j).
c
c           zerot(i):  Row array with averaged counts for all
c             a/d channels.  This array is read by the
c             subroutine "filter" to convert to the
c             preferred 6 channels and put into zeros(i).
c
c           a(i,j):  Coefficient matrix [B] .  From {L} = [B]{R}
c
c ----- Files:
c         mame:  Raw MIT counts file with data from all
c         a/d channels
c
c         Ratio: file of Convair R-cal/MIT R-cal readings for the
c              6 preferred channels.
c
c         M2X1.DAT:  Balance coefficients for Roll bridge 2 and
c           Axial bridge 1.
c
c         Testout:  Loads from test runs, uncorrected for zeros.
c
c
c         *** Data Conventions Used in This Code ***
c
c            IndexReadings()Loads()
c             1Normal Force 1Normal Force at center
c             2Normal Force 2Pitch Moment at center
c             3Side Force 1Side Force at center
c             4Side Force 2Yaw Moment at center
c             5Selected Roll BridgeRoll Moment at center
c             6Selected Axial BridgeAxial Force at center
c
c         ( The zeros() and ratios() vectors use the same conventions as
```

```
c          the pdata() )
c
c ---------------------------------------------------------------------

          integer*2 m
          real pdata(6), loads(6), zeros(6), ratios(6), fdata(16)
          real zerot(16), angle
          character*10 tcase, zcase
          character*11 fname, lname, rname
          character*80 header, id
          character ans
          m=0

c ----- open files
          open (unit=10, file = 'ratio' , status = 'old' )

          write (*,*)
          write (*,*) '          *** PROGRAM MAINTST.FOR *** '
          write (*,*)

cdb --- Debug commands for reading in Convair test case. This is to
cdb       check the data reduction algorithm .....
cdb       goto 52

          write (*,*) ' Note:  The program needs the name of the zeros'
          write(*,*) '     file for this coning angle. This should '
          write(*,*) '     be something like HFaa.ZER (not .CTS).'
          write (*,*)
          write (*, ' (A\) ' ) ' Input the zero file name (HFaa.ZER): '
          read (*,1) fname
1         format(A11)
          write (*,*)

c ----- Read in zeros from file fname
          open (unit = 2, file = fname , status = 'old')
          read (2,'(a80)') header
          read (2,'(a80)') id
          read (unit =2, fmt = 2, err = 51) angle, (zerot(i) , i = 1,9)
2         format ( F6.2, 9F7.1)
          write (*,*)
          write (*,*) ' Zeroes read in successfully! '
          write (*,*)
c -----Debug command
          write (*,*) zerot(1),zerot(9)
          goto 52
51        write (*,*)
          write (*,*) ' Error in reading zero file '
          goto 100
52        continue

c ----- Read in ratios from file of preferred channels (file "RATIO")
          read (unit = 10, fmt = 6, err = 55) (ratios(i) , i=1,6)
6         format (6F8.4)
          write (*,*)
          write (*,*) ' Ratios read in successfully'
c -----Debug command
          write (*,*) ratios(1),ratios(6)
          goto 56
55        write (*,*) ' Error in reading in ratios'
          goto 100
56        continue

cdb --- Debug for reading in Convair test case ....
cdb       goto 57

c ----- Call filter subroutine for producing zeros(i)
          call filtz (zerot,zeros)

57        continue

c ********************** Data Reduction Portion **************************


c         ... assign a vacant FORTRAN unit number ...
          lunit = 3
c         ... use the CONVAIR preferred set of coefficients (R2X1) ...
          item = 4
          call intcoef( lunit, item  )
          Write (*,*) ' Coefficient Data has been read '

c         ... these are the A/D readings without applied external forces
          call setzero( zeros )
```

```
c       ... these are the ratios of the current signals divided by the ...
c       ... original signal levels at calibration ...
        call setrcal( ratios )

        write (*,*)
        write (*,'(A\)') ' Input the load ouput file name (HFa00.LOD):'
        read (*,1) lname
        write (*,*)

        open(unit=7, file = lname, status = 'new' )
        write (7,10)
10      format(1X,'TC',3X,'Z',8X,'M',8X,'Y',8X,'N',8X,'K',
     +    8X,'X')

cdb --- Debug for reading in Convair test case .....
cdb ---  goto 58

c ----- Go to data taking subroutine
80      Call quickrd(fdata,tcase,m)

        write (*,*) ' quickrd done '
c ----- debug command
cdb     pause
        goto 62

cdb --- Debug for reading in Convair test case .....
58      continue
        write (*,*)
        write (*,' (A\)') ' Input PREVIOUS raw counts file: '
        read (*,1) rname
        write (*,*)
        open (unit=9, file = rname, status = 'old')
        read (unit = 9, fmt = 59, err = 61) tcase, (fdata(i), i=1,9)
59      format (a10, 9F7.1)
        write (*,*) ' Previous counts .....'
        write (*,*) fdata(1), fdata(9)
        do 60 j = 1,6
          zeros(j)=0.0
60      continue
        goto 62
61      write (*,*) ' Error in reading Previous counts....'
62      continue

c ----- Call filter subroutine to reduce the readings to the preferred
c       6 channels (i.e. read in data to pdata(i))
        call filter(fdata, pdata)

        write (*,*) ' filter done '
c ----- debug command
cdb     pause

        write (*,*)
        write (*,*) '   Now Processing Data!!! '
        write (*,*)

c       ... adjust the values by removing the zeros and compensating ....
c       ... for the ratio of the signal level ...
        call doadjus( pdata )

        call doload( pdata, loads, ierr )
        if( ierr .ne. 0 ) then
          write(6,12) tcase
 12       format(' Convergence problem on point ',A10)
          endif

        write(7,7) tcase, (loads(i), i=1,6)

 20     continue

c ---- Write loads to screen
        write (*,*)
        write (*,*) '  Loads for this run... '
        write (*,*)
        write (*,10)
        write (*,7)  tcase, (loads(i) , i=1,6)
7       format (A3, 6F9.4)

        write (*,*)
90      write (*,'(A\)') ' Would you like another test run? (y/n) : '
        read (*,fmt =9, err = 90) ans
9       format (A1)
        m=m+1
        if (ans .EQ. 'y') goto 80
```

```
      close(unit = 10)
      close(unit = 7)
      close(unit = 1)
100   continue
      end
```